

Modeling of Adaptive Energy Absorbing Steering Columns for Dynamic Impact Simulations

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ABSTRACT

The objective of this paper focused on the modeling of an adaptive energy absorbing steering column which is the first phase of a study to develop a modeling methodology for an advanced steering wheel and column assembly. Early steering column designs often consisted of a simple long steel rod connecting the steering wheel to the steering gear box. In frontal collisions, a single-piece design steering column would often be displaced toward the driver as a result of front-end crush. Over time, engineers recognized the need to reduce the chance that a steering column would be displaced toward the driver in a frontal crash. As a result, collapsible, detachable, and other energy absorbing steering columns emerged as safer steering column designs. The safety-enhanced construction of the steering columns, whether collapsible, detachable, or other types, absorb rather than transfer frontal impact energy. Recently, more advanced steering column designs with adaptive features, mechanically or pyrotechnically activated, have been introduced for different crash conditions, including different crash severity, occupant mass/size, seat position and seatbelt usage. These steering columns are able to absorb different impact load conditions ranging from high impact load for larger and/or unbelted crash dummies (95th-male and 50th male, respectively) in higher severity crash tests to low impact load for smaller (5th female dummy) and/or belted drivers in lower severity crash tests. With the steering column designs becoming more complex, the modeling of a steering column with advanced safety features also becomes more challenging.

To optimize prototype testing and enable faster development cycle time, an attempt was made to model the steering assembly with advanced safety features. The modeling study was divided into two phases, with the first phase focusing on the modeling of an adaptive energy absorbing steering column as discussed in this paper. The modeling of an advanced steering assembly, with a safety-enhanced steering wheel and an adaptive energy absorbing steering column for frontal and side impact simulations, was developed in the second phase of the study and will be presented separately [1]. To provide information for modeling methodology development, component and sub-system tests were developed and conducted to understand the mechanical behaviors of different energy absorbing features as well as the performance of the adaptive mechanism in the steering column design. Different dynamic impact speeds, including quasi-static tests, were also included in DOE test matrices so that collapse speed sensitivity of the steering column components could be obtained. Finite element modeling methodology was developed and presented based on its correlations with the steering column component and sub-system tests.

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INTRODUCTION

A single-piece steering column (Figure 1), consisting of a long steel rod, was commonly designed to connect the steering wheel to the steering gear box before the 1950s. With the single rod design, when a frontal collision occurred, the steering column would often be pushed rearward towards the driver. At the same time, the driver would move forward, due to his inertia, and hit the rigid steering assembly. Based on this kinematics, engineers identified the need for steering column designs with energy dissipation capabilities. The automotive

industry started designing and developing energy absorbing steering assemblies in the late 1950's [2, 3]. New designs, such as collapsible (Figure 2), detachable (Figure 3), and other energy absorbing steering columns (Figure 4), were invented to prevent the rearward displacement of the column in crashes. Many collapsible steering columns are composed of an inner and an outer sleeve pressed tightly together with indentations, steel bearings, or strong resin, designed to control collapse load and distance. In the event of a frontal impact, the outer sleeve would move further into the inner sleeve in a piston fashion to absorb impact energy. A detachable steering column

with a decoupler in the middle of the steering shaft allows the steering column to detach when the impact load exceeds a designed level. The safety-enhanced constructions of the steering columns, whether collapsible, detachable, or other types, absorb frontal impact energy by collapsing or breaking upon impact.



Figure 1. Single-piece steering column design.

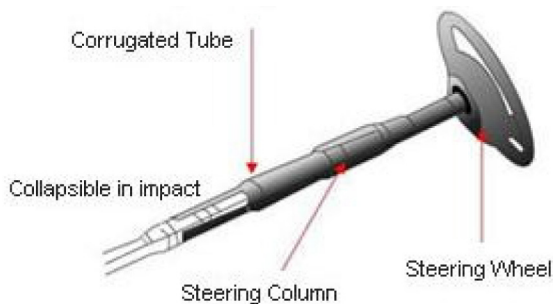


Figure 2. Example of collapsible steering system design.

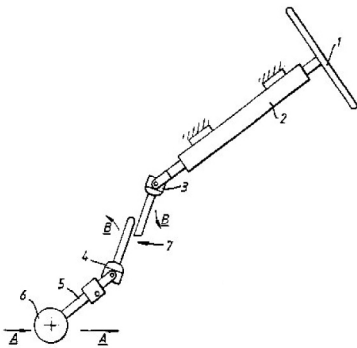


Figure 3. Example of detachable steering system.



Figure 4. Examples of energy absorbing steering column.

The Society of Automotive Engineers (SAE), recognizing the need for a test procedure to evaluate the characteristics of steering systems, issued Recommended Practice J944 [4, 5] in 1965. This procedure consists of a body form (also known as body block or black tuffy) weighing 75 pounds (34.02 kilograms) that impacts a steering assembly mounted in the production configuration. A load cell mounted between the wheel and column is instrumented to measure the force imparted to the system. In 1996, the General Services Administration (GSA) created criteria for testing the performance of steering assembly under controlled conditions. The performance criteria were issued as GSA Standard 515/4a [6] and became effective in October 1967. The standard required that the force imparted to the SAE J944 body form must not exceed 2,500 pounds (11,121 Newton) when impacting the steering assembly at 15 mph (6.71 m/s). The standard also required that the rearward horizontal displacement of the upper end of the column must not exceed 5 inches (127 mm) during a 30 mph (13.41 m/s) frontal barrier test. In 1967, National Highway Traffic Safety Administration (NHTSA) adopted the GSA standard but separated the energy absorption and rearward displacement requirements into two standards, FMVSS (Federal Motor Vehicle Safety Standard) 203 [7] and FMVSS 204 [8]. The two standards, applying to all passenger cars sold in the United States, became effective on January 1, 1968. FMVSS 203 [6] specifies requirements to minimize chest, neck, and facial injuries by providing steering systems that yield forward, cushioning the impact of the driver's chest by absorbing much of this impact energy in frontal crashes. FMVSS 204 [7] specifies requirements limiting the rearward displacement of the steering control into the passenger compartment to reduce the likelihood of chest, neck, or head injuries. The FMVSS 203 and FMVSS 204 standards were subsequently extended to light trucks and vans effective September 1, 1981[1].

Similar to FMVSS 203 and FMVSS 204, the ECE R12 [9], consisting of three annex tests, was introduced in Europe to cover the crash performance of the steering system. The three annex tests were designed to limit the injury risk to an occupant when contacting the steering system during a frontal impact. Annex 4 was designed to limit the displacement of the steering column relative to the vehicle in a 30 mph (13.41 m/s) full frontal test.

Annex 5 was designed to limit the forces on the driver's chest in a 15 mph (6.71 m/s) body form test against the steering system. Annex 6 was designed to limit the forces on the driver's head in a 15 mph (6.71 m/s) head form test against various points on the steering wheel.

Improved steering columns have been designed to comply with these standards since 1970. To understand the performance of several ball-sleeve energy absorbing steering columns, Horsch and Culver [10] designed and conducted a series of Hyge sled tests with different column mounting angles and different dummy sitting postures. From the steering assemblies and test conditions studied, it was found that axial impact resulted in

almost negligible wheel deformation and the column was the main energy absorbing component. Off axis impact resulted in initial steering wheel deformation with the wheel and column sharing energy absorption. The development of energy absorbing steering systems at General Motors was documented by Horsch, Viano, and DeCou [11]. Their paper covered the early development of General Motors energy absorbing steering systems beginning with the work of the crash injury pioneers Hugh DeHaven and Colonel John P. Stapp since 1966. It also evaluated the crash performance of the system and further improvements in the protective function of the steering assembly. Many programs and studies conducted in the development of GM energy absorbing steering systems were highlighted, including: the GM safety research program, Safety Car, Invertube, the biomechanics projects at Wayne State University. In addition, the paper also documented the engineering efforts from various GM divisions, government interactions and regulations, field accident reports, and the thoracic and abdominal tolerance studies that led to the development of the Viscous Injury Criterion and self-aligning steering wheels.

Steering column movement in severe frontal crashes and its potential effect on airbag performance were investigated by Zubry and O'Neill [12]. Based on results from 106 IIHS (Insurance Institute for Highway Safety) frontal ODB (Offset Deformable Barrier) tests at 40 mph (64 km/h) and real-world accident data, the authors concluded that steering column movement in severe frontal crashes can influence airbag performance. To evaluate the effects of intrusion on steering column movement, as well as the mechanics of the steering column movement during frontal impact tests, Fileta and Liu [13] conducted static crusher testing using the front part of a midsize front-wheel drive vehicle as the baseline design for test structures. A static crusher testing approach was used in accordance with a test matrix that included eight different tests. Four primary factors, "rail into dash-panel", "subframe into toe-board", "shotgun/shock tower into cowl", and "powertrain into dash-panel", were selected as the first four tests in order to study their effects on the steering column movement separately. The interactions between these primary factors were also studied by conducting three tests, which have the combined effects of two factors. Additionally, the last test case was conducted to study the effect of combining three factors. This study found that the "rail into dash-panel" had the strongest effect on the upward displacement of the steering column. The brake pedal bracket and the steering intermediate shaft were found to push against the lower end of the steering column in the "rail into dash-panel" test. Based on this finding, a sensitivity study was performed to evaluate different designs of column support. The upward displacements of steering column obtained from three designs with different "cross-car beam mounted" supports were found to be lower than that of the traditional "cowl mounted" support. The steering column research conducted by many automotive safety experts has helped greatly in understanding of the role of the steering column in occupant safety. As a result, different energy absorbing steering systems, such as [14, 15, 16, 17, 18]

described in other articles and patents, have been developed and safety-enhanced steering systems are now being widely used in vehicles.

Finite element analysis (FEA) tools have been used extensively in the automotive industry to evaluate structural performance. However, the finite element studies related to modeling steering columns have been rather limited due to the complex designs of different energy absorbing features and adaptive mechanisms. Gotoh et al. [19] made the first attempt to use FEA to model the collapse behavior of a steering column in 1992. A thin steel plate able to bend and tear was designed as an energy absorber in the steering column studied. A ductile fracture model with boundary spring elements was adopted to simulate the bending and tearing of the thin steel plate. In 2003, Kubota [20] made another attempt to model a collapsible steering column with a breakable resin pin. Static tests were conducted to obtain the loads needed to break the pin and to overcome the friction of the column shafts. The loads were converted to equivalent shearing loads and included in a bar element. Hamid et al. [21, 22] modeled an energy absorbing device in an adaptive steering column. The energy absorbing device was composed of a metal strap and a pin. During the column stroke, the metal strap is drawn over the pin which controls the deformation and the collapse load. A dynamic strap pull test was conducted for the correlation of the finite element model. The correlated finite element model was then used to investigate the effects of the metal strap with different thicknesses, widths, geometries, and friction coefficients. Liu et al. [23] studied a crushable energy absorbing device fitted inside the shafts of a collapsible steering column. Finite element simulations were conducted to correlate with two body form tests, impacting with the steering wheel and with the steering wheel-column assembly. The performance of the crushable energy absorbing device, with different hole-opening patterns, was assessed by using the correlated finite element model. Lee et al. [24] modeled a collapsible steering column with a breakable "capsule pin", a "curling plate-pin", and a "collapse ring". The mechanism is more complex, combining the design concepts from those of Kubota [20] and Hamid et al. [21, 22]. Tied contact and a stress based failure criterion were adopted to model the fracture of the plastic "capsule pin". Similar to the metal strap used in Hamid et al. [21, 22], the thickness, width, and geometry of the curling plate control the collapse load of the steering column. The friction coefficient was adjusted in the "curling plate-pin" model to correlate with the F-D curve obtained from the static curling plate pull test. The collapse load also depends on the pre-stressed "collapse ring" which was modeled with "INITIAL STRESS SHELL". A detachable steering linkage [25] also has been used to decouple the steering column, which can be modeled by using a simple approach described by Valentin and Makowski [26]. Recently, Jeoung [27] modeled a steering column component made of carbon fiber reinforced plastic (CFRP) by adopting a failure criteria developed by Tan and Shun [28] for fibrous anisotropic materials.

In order to avoid the challenges mentioned above, steering system models are usually simplified in full vehicle crash simulations. In addition, sled or subsystem models are adopted to assess occupant responses in the frontal impact crash modes. Kovacic et al. [29] proposed a simplified FMVSS 208 model and a sled model to evaluate occupant safety performance. Jeon et al. [30] designed the folding pattern and tear seam of an airbag by using subsystem simulations. Brown et al. [31] developed methods to simplify finite element simulations for frontal occupant and restraint system assessments. To save simulation time, coupling methods using calculations from both a finite element program (LS-DYNA) and an occupant analysis program (MADYMO) have also been performed regularly. Gunasekar et al. [32] developed a LS-DYNA and MADYMO coupled model to simulate the IIHS frontal offset crash test. Musale et al. [33] proposed a "Versatile Occupant Analysis Model" with coupling of LS-DYNA and MADYMO calculations to design restraint systems and optimize interior components. Linking CAD (Computer Aided Design) and CAE (Computer Aided Engineering), Canadas et al. [34] presented an integrated process for occupant safety simulations requiring LS-DYNA and MADYMO coupled calculation.

Recently, advanced steering column designs incorporating adaptive (or active) features, mechanically or pyrotechnically activated, have been introduced for impact conditions beyond the requirements of FMVSS 203 and 204, such as those required in FMVSS 208. These advanced steering columns can accommodate different crash severities, occupant masses or sizes, impact speeds, seat positions, and seatbelt usages. For example, a 95th male unbelted occupant in a high speed collision would create a much higher impact force than that of a 5th female belted occupant in a lower speed collision. These advanced steering columns are designed to absorb the energy levels of various impact conditions. With steering column designs becoming more complex, the modeling of a steering column with advanced safety features becomes more challenging.

In this study, an attempt is made to model the details of an advanced steering column with adaptive energy absorbing features. The final goal is to use the developed modeling methodology in computer simulations to aid in the achievement of vehicle safety targets, optimize prototype testing, and enable faster development cycle time. To accomplish this goal, component and sub-system tests were developed and conducted to understand the mechanical behavior of different parts as well as the performance of the different safety-enhanced steering column features. Various dynamic impact speeds, including quasi-static tests, were included in the test matrix so that the speed sensitivity of the steering column assembly can be obtained. Finite element modeling

methodology was developed and presented based on the results obtained from the component and sub-system tests.

STEERING COLUMN ASSEMBLY

The advanced steering column assembly chosen in this study is composed of several main components, including a steering column, sliding portion, BTS (Bend Tear Sheet), pyrotechnically activated pin, fixed housing, telescope/tilt adjustment mechanism, and an intermediate shaft. The main components are identified in [Figures 5](#) and [6](#), showing the steering column assembly mounted in a test fixture. As mentioned, the final goal of this study is to enhance occupant performance assessment capabilities by using the developed modeling methodology in computer simulations. As a result, all the components that can affect the occupant response need to be included. Although the telescope/tilt adjustment mechanism has no significant influence on the occupant response (except for stiffness contribution), removing it would affect the fit of the assembly.

Therefore the telescope/tilt adjustment mechanism was kept in the steering column assembly tests and finite element simulations.

In addition to the BTS and pyrotechnically activated pin, many small features were designed in the sliding portion and fixed housing to automatically adjust the energy absorbing level of the steering column assembly for different impact conditions. Both the sliding portion and the fixed housing were made out of AM 50 magnesium alloy. Small friction bumps (in [Figure 7](#), also called friction interference) and sliding tracks designed in the fixed housing, an adhesive applied to the sliding portion (in [Figure 5](#)), and the press fit between the sliding portion and the fixed housing control the initial collapse load of the steering column. The constant (BTS controlled) collapse load of the steering column assembly can be adjusted according to occupant size. The pyrotechnically activated pin can engage or disengage the BTS to increase or decrease the constant collapse load. The BTS, shown in [Figure 8](#), has four grooves that control which portions of the sheet to tear and deform during column collapse. When the pin is engaged, the two outer most grooves will tear and allow a larger portion of the sheet to deform. When the pin is disengaged, all four grooves will tear and allow a smaller portion of the sheet (two strips) to deform. As a result, a higher load would be required to collapse the column when the pin is engaged. On the other hand, a lower load would be required to collapse the column when the pin is disengaged. The shape and depth of the grooves can affect the tearing of the BTS. In addition, the collapse load is also influenced by the thickness, material, and the geometry of the BTS, including the holes in the center of the sheet and at the end of the grooves.

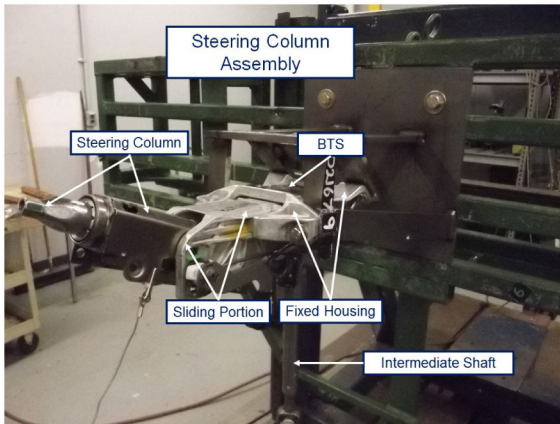


Figure 5. Steering column assembly.

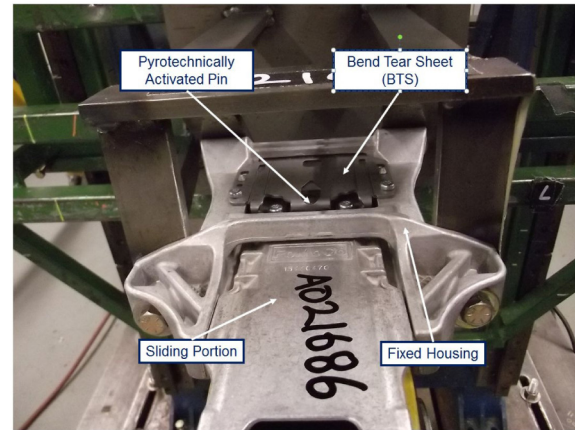


Figure 6. Adaptive energy absorbing features.



Figure 7. Fixed portion.



Figure 8. BTS.

COMPONENT AND SUBSYSTEM TESTS

To understand the responses of the adaptive energy absorbing steering column and to obtain reliable data for model methodology development, a total of ten tests (ten sets of tests each with three repeats) were designed and conducted in the first phase of this study. The ten tests are divided into two groups with the first group focusing on the BTS's behavior (Table 1) and the second group on the column's behavior (Table 2). As can be seen in Figures 9 and 10, two rigid test fixtures were designed in this study for quasi-static and dynamic tests. The quasi-static tests were conducted using a

hydraulic powered loading device (Figure 9), whereas the dynamic tests were conducted using a gas fired impactor (Figure 10). The steering column assembly was bolted (tightened to nominal torque) to the test fixture to simulate its normal in-vehicle attachment to the IP (Instrument Panel) structure. Additionally, the steering column assembly was set to the midpoints of tilt and telescope (mid/mid position) for every test. A load cell, an accelerometer, and a contact switch were mounted to the impactor so that the force-deflection data for each test could be obtained. The devices are accurate to within 1 N, 1 mm, and 1 ms.

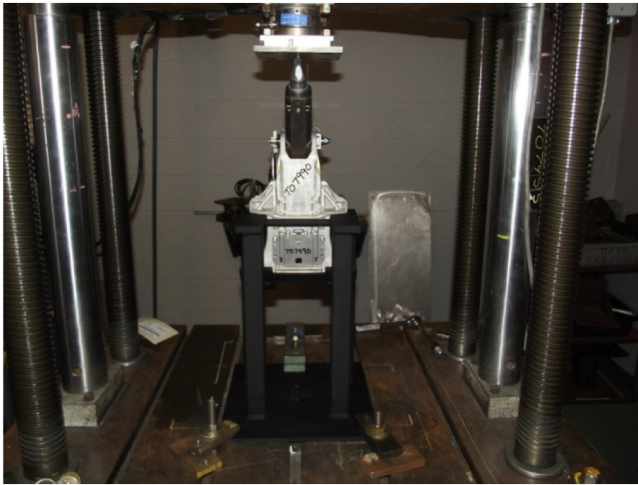


Figure 9. Quasi-static test.

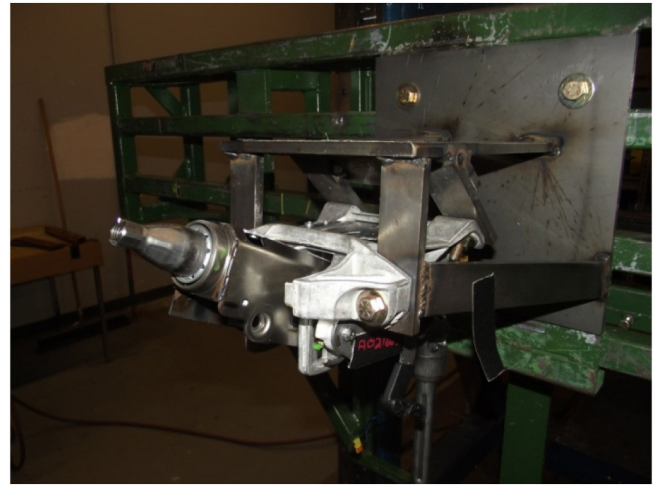


Figure 10. Dynamic test.

Table 1. BTS performance test.

Test # (Run #)	BTS Condition	Impact direction	Impact Speed	Impact Mass (Sample Size)
1 T07988 T07989 T07990	With BTS (no friction bumps) (low load, pin disengaged)	Forward	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
2 A021667 A021668 A021669	With BTS (no friction bumps) (low load, pin disengaged)	Forward	17.66 mph 18.08 mph 18.08 mph	20 Kg/44.95lbs (3)
3 T07991 T07992 T07993	With BTS (no friction bumps) (high load, pin engaged)	Forward	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
4 A021675 A021676 A021677	With BTS (no friction bumps) (high load, pin engaged)	Forward	15.99 mph 15.97 mph 16.03 mph	40 Kg/87.35 lbs (3)

The loading condition for the BTS performance test is summarized in [Table 1](#) with four tests which include two quasi-static tests (Test no. 1 and 3) and two dynamic tests (Test no. 2 and 4). The collapse load of the column is controlled by the engagement of a pin with the BTS through a pyrotechnically activated design. As shown in [Table 1](#), both “pin-disengaged” (Test no. 1 and 2) and “pin-engaged” (Test no. 3 and 4) conditions were considered to obtain the different load levels needed to collapse the steering column assembly. Since the purpose of the tests is to characterize the BTS performance, the friction bumps in the fixed housing were all

mechanically removed (illustrated in [Figure 11](#)) prior to the tests. For each dynamic test condition, the impact speed and mass were adjusted through setup runs to make sure the BTS could bend and tear fully. The finalized impact speed and mass for each dynamic test are summarized in [Table 1](#) (column 4 and 5). To include test variation, each test condition was repeated three times. Shown in [Figure 11](#) as an example, the weight of each component was also recorded and used to check the corresponding finite element model created in this study.

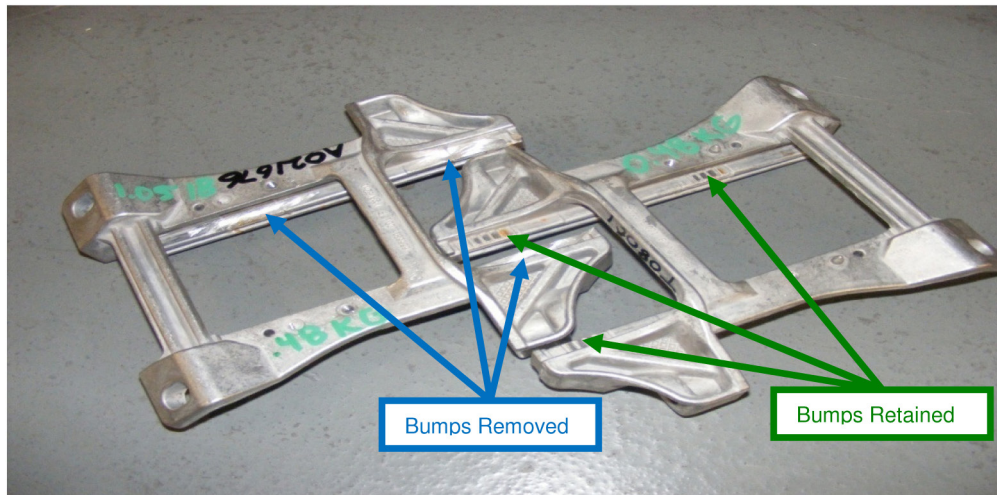


Figure 11. Fixed housing with friction bumps removed and retained.

Table 2 summarizes the loading condition for the steering column assembly performance test, including three quasi-static cases (Test no. 1, 3, and 5) and three dynamic cases (Test no. 2, 4, and 6). The main purpose of the second group of tests was to obtain the responses of the steering column assembly under different impact conditions. Similar to the first group of tests, both “pin-disengaged” (Test no. 1 and 2) and “pin-engaged” (Test no. 3 and 4) conditions were considered to obtain the different load levels needed to collapse the steering column assembly. The friction bumps and the surrounding adhesive are designed to control the load required to initiate

the steering column collapse. To obtain the load initiation without the influence of the BTS, test conditions with the BTS removed (Test no. 5 and 6) were included in the second group of tests. Figures 12 and 13 illustrate the quasi-static and dynamic tests with the BTS removed. The impact speed and mass for each dynamic test were adjusted through setup runs to make sure the steering column assembly could collapse fully. The finalized impact speed and mass for each dynamic test are summarized in Table 2, columns 4 and 5. Each test condition was repeated three times, which is the minimal sample size to obtain test variation information.

Table 2. Steering column assembly performance test

Test # (Run #)	BTS Condition	Impact Direction	Impact Speed	Impact Mass (Sample Size)
1 T07994 T07995 T07996	With BTS (pin disengaged, low load)	Forward	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
2 A021679 A021680 A021681	With BTS (pin disengaged, low load)	Forward	12.92 mph 12.96 mph 13.03 mph	40 Kg/87.35 lbs (3)
3 T07997 T07998 T07999	With BTS (pin engaged, high load)	Forward	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
4 A021682 A021683 A021684	With BTS (pin engaged, high load)	Forward	18.04 mph 18.14 mph 18.15 mph	40 Kg/87.35 lbs (3)
5 T08000 T08001 T08002	No BTS	Forward	100+/-2 mm/min (4 in/min) (Quasi-static)	n/a (3)
6 A021671 A021672 A021673	No BTS	Forward	10.05 mph 10.03 mph 9.98 mph	20 Kg/44.96 lbs (3)

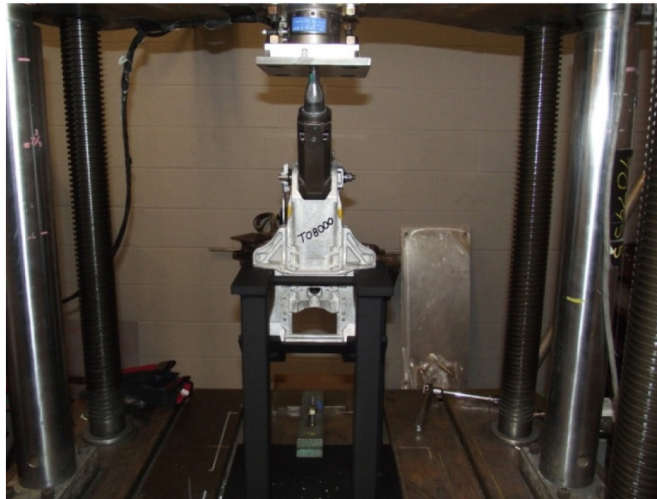


Figure 12. Quasi-static test without BTS.



Figure 13. Dynamic test without BTS.

MODELING METHODOLOGY

The final finite element model developed for the steering column assembly is shown in Figure 14a with the components discussed above. The steering column assembly model is composed of 40 parts with 56,149 nodes, 67,697 elements, 16,990 shells, 1,532 beams, and 49,175 solid elements. Formulation 16 in LS-DYNA, the fully integrated shell element, was adopted for all shell element calculations in computer simulations.

Formulation 1, the default, was chosen for all solid element calculations. The finite element model was finalized through extensive iterations to correlate with the component and subsystem tests which will be discussed later. The sliding portion and the fixed housing were made out of AM magnesium alloy. The modeling of magnesium components is not straight forward due to the associated die casting processes. Inhomogeneous micro-structures are usually found in die cast components. Most die cast components contain an outer surface with dense small grains and an inner core with

considerably more pores. Various process parameters such as the melting temperature, die cooling system, injection speed, die lube spraying time, and the vacuum system can be adjusted to reduce the porosity in die-cast magnesium alloys. As a result, the mechanical properties of magnesium components are highly affected by their microstructures and local porosities. In this study, an AM 50 material model, developed with consideration of a casting process through separate projects, was used as a baseline. Additional adjustment was made to the baseline material model during the correlation process to make sure it can correlate with all component and subsystem tests. The boundary condition in each test was also found to be crucial in achieving good correlation. The impactor and test fixture designed in this study were modeled (shown in Figure 14b) in accordance with their geometries and dimensions. The material models with failure criteria and strain rate dependency for the steel components in the steering column assembly, impactor, and test fixture were defined based on their corresponding grades. Material type 24 (*MAT PIECEWISE LINEAR PLASTICITY) was adopted to model the magnesium alloy and all steel components so that

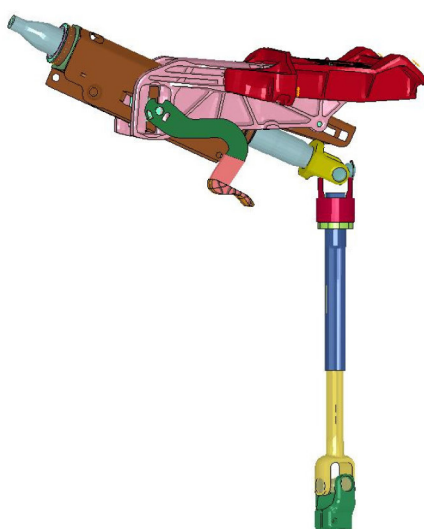
more accurate strain rate data could be provided. The beam elements were modeled using Material type 196 (*MAT GENERAL SPRING DISCRETE BEAM).

In addition to the material constitutive laws and boundary conditions, the mesh patterns of several critical components play very important roles in the correlation process which led to the final model. These critical components include the BTS, fixed housing, and sliding portion. Extensive iterations were conducted in this study to investigate the sensitivity of mesh size, mesh patterns, approximation of small geometric features, and element types to the predicted collapse load. The main lessons learned in the development of the mesh systems for these critical components are discussed and summarized below.

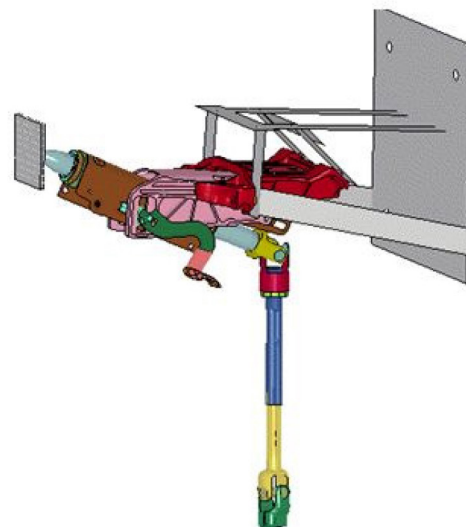
In the initial development stage, hexahedral 8-node solid elements (also called 8-node brick element, Hexa 8-node element, or HEXA8 element) were used to model the BTS which can tear and deform differently depending on impact conditions. As described previously, four grooves and several holes were designed in the BTS to control the collapse load. To capture the thickness change of the grooves, the hexahedral 8-node solid elements were the best candidate. Using an existing modeling practice for full vehicle simulations, the BTS Page 11 of 39 model (Figure 15a) with an average element size of 4.0 to 5.0 mm and grooves ignored entirely was created as the baseline. Knowing that the grooves cannot be ignored in the component and sub-system simulations, the groove features were added to the baseline as shown in Figure 15b. The predicted bend radii of the BTS from initial simulations

were found to be greater than those of the tests. To improve the deformation mode of the BTS, the mesh system was refined with a 1.0 mm element size. As shown in Figure 15c, the refined element size also allowed the geometries of the holes to be captured more accurately. Although the refined mesh did improve the prediction of the BTS deformation mode, the predicted bend radius was found to be non-uniform and slightly greater than those of the tests. Subsequently, the BTS was re-created with a uniform mesh pattern (Figure 15d), which required tedious adjustments in many local areas. The simulations conducted by using the uniform mesh pattern resulted in a much improved prediction of the BTS deformation mode.

Although the adoption of Hexa 8-node solid elements to model the BTS had achieved satisfactory results, the computation time in the component simulations was longer than desired. To improve computation efficiency, the Hexa 8-node solid elements were replaced by shell elements as shown in Figure 16a. In addition, a more refined mesh with 0.5 mm average element size (Figure 16b) was also created to investigate the sensitivity of the shell element mesh size. The simulation results obtained from both shell element mesh systems, 1.0 mm and 0.5 mm average element sizes, were found to be very similar to that of the solid element mesh system with a 1.0 mm average element size. The simulation with a 1.0 mm shell element mesh system requires much less computation time compared to those of 1.0 mm solid element mesh system. Considering computation efficiency and accuracy, the shell element mesh system with a 1.0 mm average element size was found to be optimal and used in subsequent simulations.



(a) Steering column assembly model.



(b) Impactor and test fixture models.

Figure 14. Finite element models: Steering column assembly without and with impactor and test fixture.