Technical Paper

Controlling Loading Dynamics in Chassis Bolted Connections Through Friction Increase

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Abstract

With the trend towards electrification, vehicle chassis designs are evolving. The number of vehicle variants (ICE, hybrid, BEV) for a like model are increasing and, in the case of BEVs, there are multiple models utilizing the same skateboard design. These vehicle variants can present challenges of how to handle the differences in weight and loading dynamics while utilizing the same or similar carry-over chassis designs.

In some cases, this problem can be solved by increasing the shear capacity of the critical bolted connection. This can be done by increasing the static coefficient of friction between the mating components. This paper presents FEM results on the effects of 3M™ Friction Shims, a friction enhancement solution, on shear capacity of a weight-bearing connection in a vehicle chassis. The average increases in force withstood by the connection before slippage were as follows: 44% from increasing bolt size; 15% from moving to a higher material class; 395% from adding 3M™ Friction Shims. This demonstrates that 3M™ Friction Shims can significantly increase the shear capacity of a bolted connection without requiring significant design changes. The solution is effective on common material types including aluminum and e-coated steel.

Introduction

Changes in Vehicle Design

Powertrain and chassis design has been rapidly evolving in recent years. It is becoming increasingly common to see multiple powertrain variants for the same model of vehicle, i.e., ICE, hybrid, or BEV. These variants inherently present challenges of managing the loading differences on the bolted connections, both with differing weight distributions and total curb weight of the vehicle for the same carry-over chassis design. Likewise, for many BEV manufacturers, it is becoming common to utilize the same skateboard style of chassis across multiple vehicle models with different body styles and maximum weights. For example, a pickup truck or delivery vehicle will see higher shear loaded joints than other smaller sized passenger models.

Lightweight materials such as aluminum and e-coated steel are commonly used throughout the vehicle chassis. Both materials present challenges for bolted connections: aluminum can deform with high clamping forces, while coated materials have low surface friction.

To address the challenges when a bolted connection exceeds its loading limit, a design change can be made to increase the bolt size or use a higher rated material grade of bolt. However, this solution will require a unique design feature or part number for a specific model variant, precluding a true carry-over design. Sometimes, a design change may not even be feasible due to limitations from other parts of the assembly. This then leaves the option to increase the friction between the mating surfaces of the bolted connections, therefore enabling the same design and part numbers to be maintained across all variants.

Friction Mechanisms

Friction describes the behavior of material surfaces that are in contact with one another and observe a loading regime. Surface interactions are based on material characteristics and mechanical interaction. There are two basic mechanisms for defining friction behavior: deformation and adhesion.

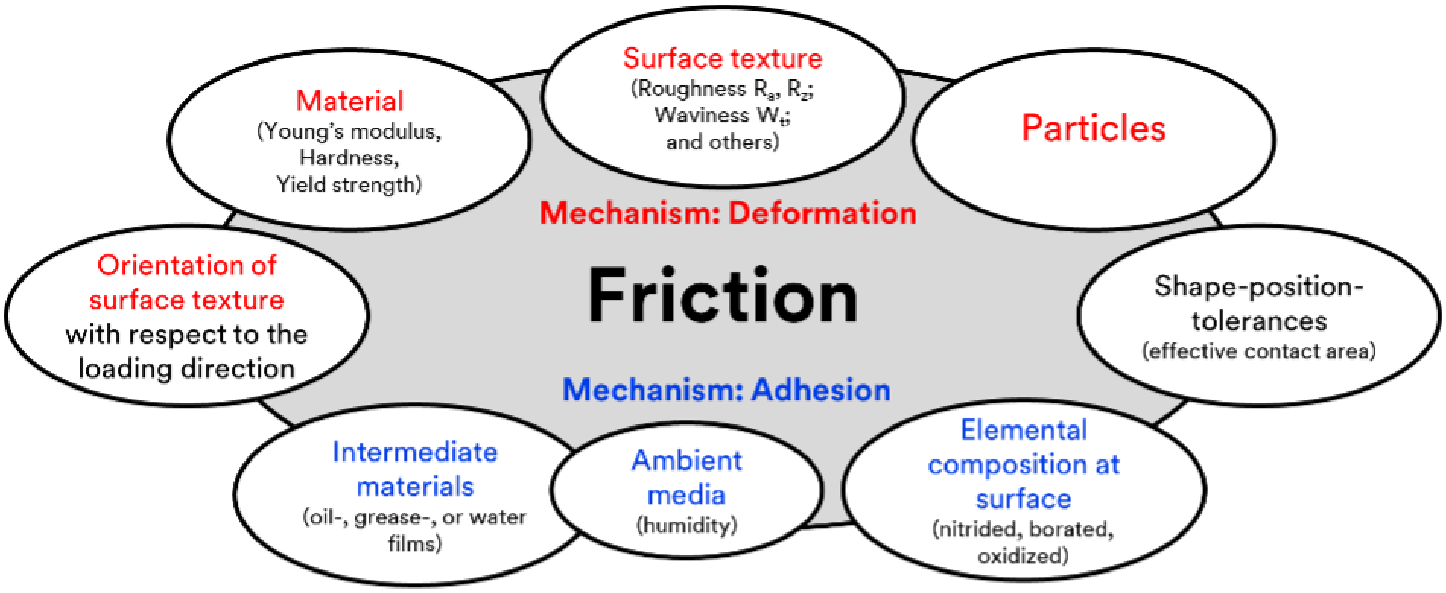

Figure 1: Parameters influencing friction mechanisms, relating to deformation and adhesion.

These parameters, detailed in Figure 1, influence the coefficient of friction of a system. Therefore, friction behavior is always a system property. The most important parameter is the material itself, as the texture of the surfaces in contact determines the size of the real contact area. Rough surfaces will have contact only with the peaks of the roughness, which decreases the real contact area and impacts the amount of mechanical interaction.

To make friction measurements meaningful, material and surface characterization is a prerequisite.

Measuring Friction and Determining the Coefficient of Friction (μ)

In addition to material properties and surface textures, the following must also be measured:

- **Normal force (F_N)** – Force that generates the contact pressure, acting perpendicular to the contact plane. To calculate the nominal contact pressure σ, F_N is divided by the nominal contact area (A_{nom}).
- **Shear force (F_f)** – Force that acts perpendicular to the normal force and can be caused by lateral or torsional loads. The shear force that is carried by the friction system is also called friction force.
- **Displacement of the two surfaces relative to each other**

Since friction behavior is a system property, it can be measured on real parts or in surrogate model tests. Often real parts are too large or expensive to be tested directly. Therefore, model tests are typically used. To perform valuable model testing, the following is needed:

- Representative samples:
  - Materials identical to the original parts
  - Processing/machining identical to original parts
  - Surface characterization, specifically surface roughness and flatness
- Precise measurement of F_N, F_f, and displacement over time

The outcome of a friction test is a friction curve that displays friction force vs. displacement. The shape of the friction curve is dependent on the test method. Three typical curves are detailed in Figure 2. It is possible to calculate the coefficient of friction μ according to Equation 1 for each point of the friction curve. In most measurements, μ is not constant. For this reason, understanding how the friction curve and test method definitions apply for characteristic values of μ is important. These definitions depend on the application and are part of the different measurement methods.

$$\mu = F_f / F_N$$

Equation 1: Determination of coefficient of friction (μ).

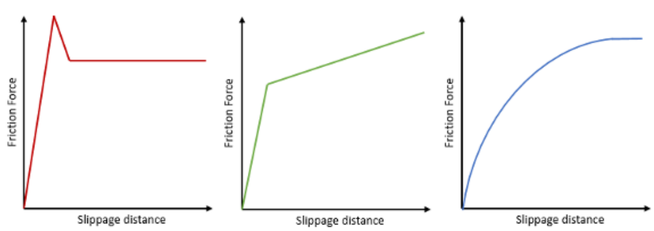

Figure 2: Example friction curves detailing how the friction force changes over the slippage distance.[1]

Definition of Static Coefficient of Friction (μ_s)

Understanding μ_s is critical, as it can be used to determine the theoretical point at which a joint will start to slip. In relation to automotive joints, μ_s can be used to describe the point at which a connection starts becoming unstable. Many different parameters (Figure 1) influence μ_s, and the definition can vary depending on the test method used. There are several different friction tests described in literature that can be used to define μ_s. Two of these methods detail testing for determining μ_s in joints of large structures (i.e., buildings, bridges).[2,3] Another method, a torsion test from the Chemnitz University of Technology, Germany, is focused on joints in smaller structures (i.e., vehicles).[4] This method is used by the certification body DNL GL (formerly Germanischer Lloyd Industrial Services GmbH) during certification tests for coefficient of friction.

In this method, two specimens of the same geometry are pressed against each other with a normal force. One specimen is fixed in its position and the second specimen is loaded with a torque and twisted until the maximum twisting angle of 5° is reached.

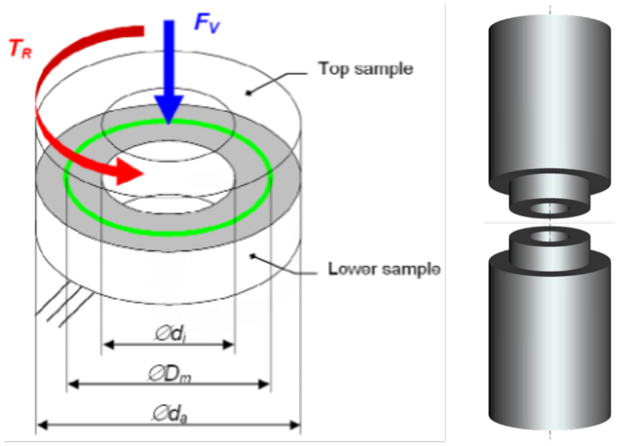

Figure 3: Load principle and geometry of the torsion test. Normal force denoted as FV.

From the friction curves generated (Figure 4), the coefficient of static friction can be determined. The initial linear behavior of the friction curve represents the elastic behavior of the materials in the test setup. The point at which the slope of the curve changes from linear (elastic behavior) to nonlinear is the point at which slippage starts. It is important to account for the elastic behavior to isolate the impact of friction at the material interface by projecting that same linear slope along the twisting angle.

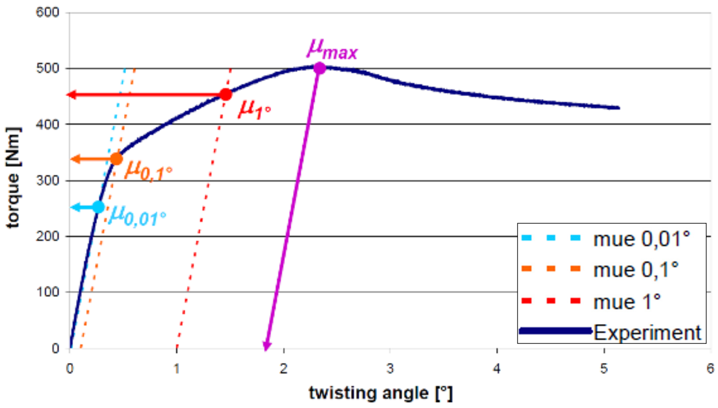

Figure 4: Friction curve detailing test evaluation at static torque load and determination of the slippage moment.

In this test method, the point of slippage on the friction curve is at $\mu_{0.1°}$. Factoring in the diameter of the specimens, the linear slippage distance for a twisting angle of 0.1° is 20 µm. The slippage distance of 20 µm is then used to determine the static coefficient of friction based on this type of friction curve.

Friction Enhancement Solutions

One option to increase friction between surfaces is to introduce a friction enhancement solution. These solutions can be dependent on the materials used in the system as some types of solutions, such as mechanical surface treatment, can also pose challenges: aluminum is deformable, while disrupting the e-coat can increase corrosion concerns.

3M™ Friction Shims help increase the static coefficient of friction between mating surfaces in bolted connections by three to five times. They consist of a nickel coated steel substrate with partially embedded diamonds that "bite" into the surface, creating a microform fit that significantly increases friction between the two mating parts. This concept is depicted in Figure 5, which illustrates the diamond particles penetrating into the counterpart surfaces after pre-load, i.e., bolt torque load, is applied. The diamond particles increase friction through several parameters, with the largest aspects being deformation from the particles sinking into the counterpart surfaces and from scraping against the surfaces when slippage starts. This solution has proven effective for all typical materials and surface conditions seen in chassis and suspensions, including steel, aluminum alloys, and e-coating.

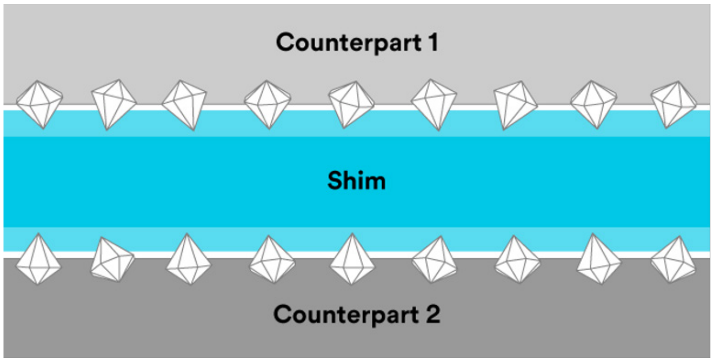

Figure 5: Cross-sectional schematic representing the function and application of 3M™ Friction Shims.

Using this method of increasing friction, finite element computer modeling can be used to predict the expected performance differences. Comparisons are made on an e-coated steel surface mating to an aluminum alloy surface with empirically derived static coefficient of friction values.

Methods

Shear Test at 3M Technical Ceramics, Kempten, Germany

3M Technical Ceramics uses a simple shear test to determine friction curves. For this test, simple cuboid specimens are clamped together by an external clamping mechanism. The center specimen is then moved relative to the two outer specimens by a compressive load acting perpendicular to the clamping force. The principle of the test setup is shown in Figure 6.

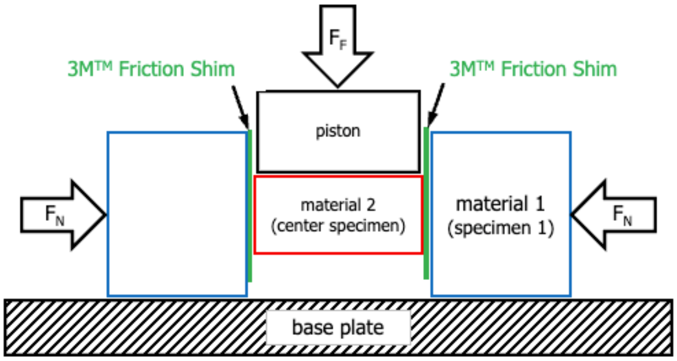

Figure 6: Measurement principle and test setup of the shear test.

Clamping force, compressive load, and displacement of the center specimen relative to the outer specimens are measured. The evaluation of characteristic values for μ_s follows the principle as described for the torsion test performed by Chemnitz University of Technology, and μ_s was determined at a slippage distance of 20 µm.

The following μ_s values were determined for use in the FEM model:

- E-coated steel to aluminum: 0.14
- E-coated steel to 3M™ Friction Shim to aluminum: 0.68

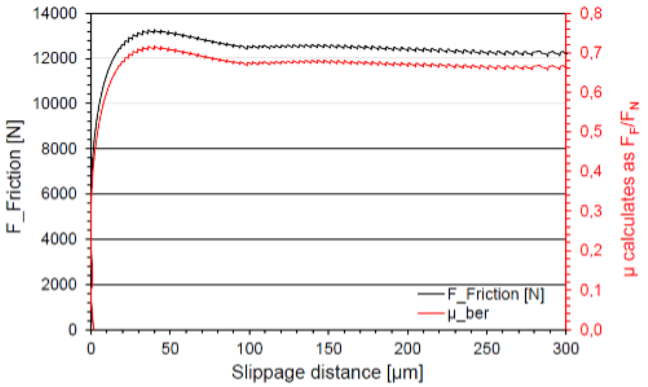

Figure 7: Friction curve for e-coated steel to 3M™ Friction Shim to aluminum.

Finite Element Method (FEM) Model of Chassis Bolted Joint

Two analyze the effect of 3M™ Friction Shims on the shear capacity of a bolted joint, a finite element model was created. The CAD model of the joint was created in Creo® software. The joint components (bolt, nut, 3M™ Friction Shim, doghouse, and strut) were modeled using a 3D solid fine mesh, primarily tetra10 elements (Figure 8). The model was built and solved using ANSYS® Mechanical™.

Typical industry standard processes and methods were used for constructing the finite element model. While this analysis was not directly correlated with test data, all the techniques followed accepted industry standards, which have historically been correlated to test data.

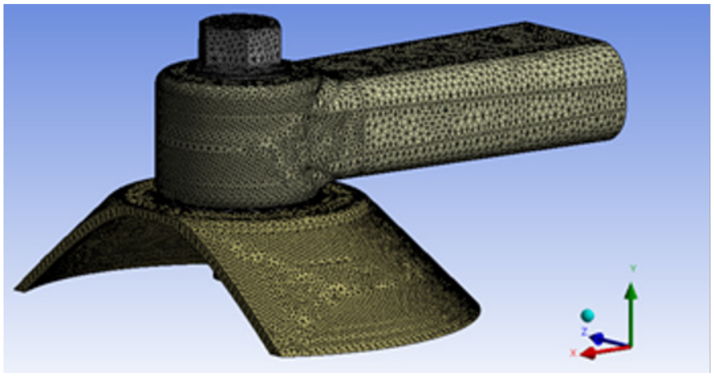

Figure 8: Finite element model mesh.

The components selected for this case study were designed to represent typical bolted connection configurations in a vehicle chassis. This case represented an aluminum strut connected by a bolt through a mounting pad mating hole to an e-coated sheet steel chassis structure. Figure 9 shows the specific geometry chosen. The aluminum mounting arm was labeled as "Al strut" and the e-coated sheet steel geometry was in a doghouse design configuration. The e-coat was represented as a frictional contact surface; it was not modeled separately due to uncertainties about adhesion, thickness, and hardness. The 3M™ Friction Shim component was placed between the aluminum strut and the e-coated steel mounting surfaces and is shown as blue in the exploded view (Figure 9b). The aluminum strut and the steel components were assigned typical material properties.

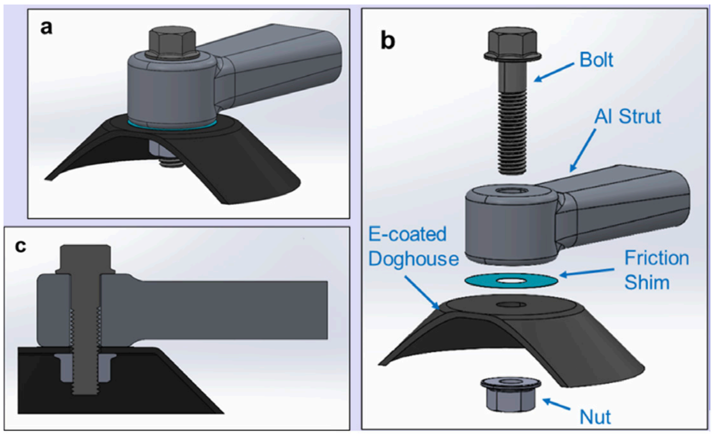

Figure 9: (a) CAD model view of the bolted connection between an aluminum strut and e-coated sheet steel "doghouse" used as the geometry for the simulation studies; (b) Exploded view of the same connection geometry with labeled components; (c) Cross-sectional view that is used in the simulation results.

The model assumed that:

- The base of the doghouse was fixed in space
- The static coefficient of friction was 0.14, based on the 3M Shear Test referenced in the Methods Section
- The static coefficient of friction was held constant throughout the analysis

When the 3M™ Friction Shim was used, the model assumed that:

- Frictional contact existed between the upper surface of the 3M™ Friction Shim and the lower surface of the strut and between the lower surface of the 3M™ Friction Shim and the upper surface of the doghouse
- The static coefficient of friction of these interfaces was 0.68, based on the 3M Shear Test referenced in the Methods Section

The model was set up with several variations, as noted in Figures 10 and 11:

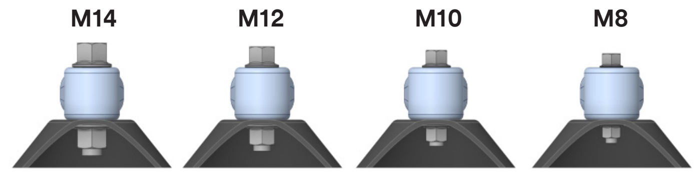

Figure 10: Model view of bolted connection detailing different sizes of bolts. Only the clearance hole size and bolt size were varied between conditions.

Nominal bolt size (mm)	Bolt material class per ISO 898-1	No 3M™ Friction Shim	3M™ Friction Shim	Clamp load (kN)	Coefficient of friction at interface	Calculated shear capacity* (kN)
M10	10.9	X		36.1	0.14	5.1
M12	10.9	X		52.5	0.14	7.4
M14	10.9	X		71.9	0.14	10.1
M10	12.9	X		42.2	0.14	5.9
M12	12.9	X		61.3	0.14	8.6
M14	12.9	X		83.7	0.14	11.7
M8	10.9		X	22.8	0.68	15.5
M10	10.9		X	36.1	0.68	24.5
M12	10.9		X	52.5	0.68	35.7

Figure 11: Table detailing each model condition based on bolt size, material class, and inclusion of 3M™ Friction Shims

**Calculated shear capacity is simply the clamp load multiplied by the coefficient of friction. This value is based on simple rigid body physics and does not take account of material elasticity.*

Each model was run in two steps:

1. It pre-tensioned (preloaded) the bolt, as appropriate for the size and class of the bolt.
2. It applied an incrementally increasing external load to the strut, normal to the red surface in Figure 12. This produced the shear stress at the joint between the strut and the fixed doghouse.

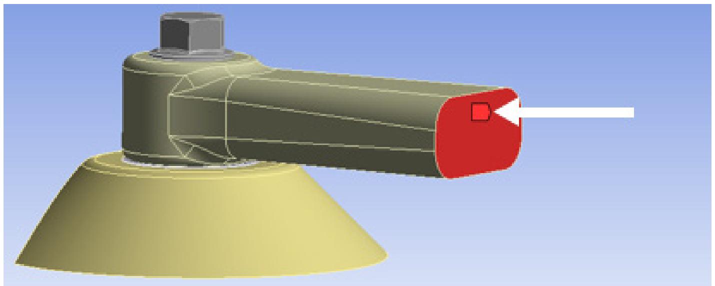

Figure 12: External load applied to strut.

The model calculated the stress and strain throughout the assembly as each increment of the load was applied. Additionally, it calculated slip of the strut relative to the doghouse. As the load increased, the joint components deformed elastically. In the friction contact areas, this deformation initially caused very little relative displacement. As the load increased, localized relative displacement occurred within the joint. Finally, when the load increased enough to overcome the friction within the joint, gross relative displacement occurs increasingly until the joint fully slipped.

Figures 13, 14, 16 show the relative slip between the strut and the fixed doghouse as the shear load applied to the strut was increased. This relative slip was measured between a finite element node at the center of the bottom of the strut and a finite element node at the center of the top of the doghouse.

Results

The raw data from the model is plotted in Figure 13. As more force is applied to the strut, slippage occurs between the two components. Depending on the construction of the connection, movement between the two components occurs at different rates but follows a similar trend for connections that do not contain a 3M™ Friction Shim.

NOTE: The information provided here is based on tests performed at a 3M laboratory facility and may be based on a limited sample size. While we believe the results are reliable, their accuracy or completeness are not guaranteed. Your results may vary due to differences in test types and conditions. This information is intended for use by persons with knowledge and technical skills to analyze, handle and use such information and is not for specification purposes.

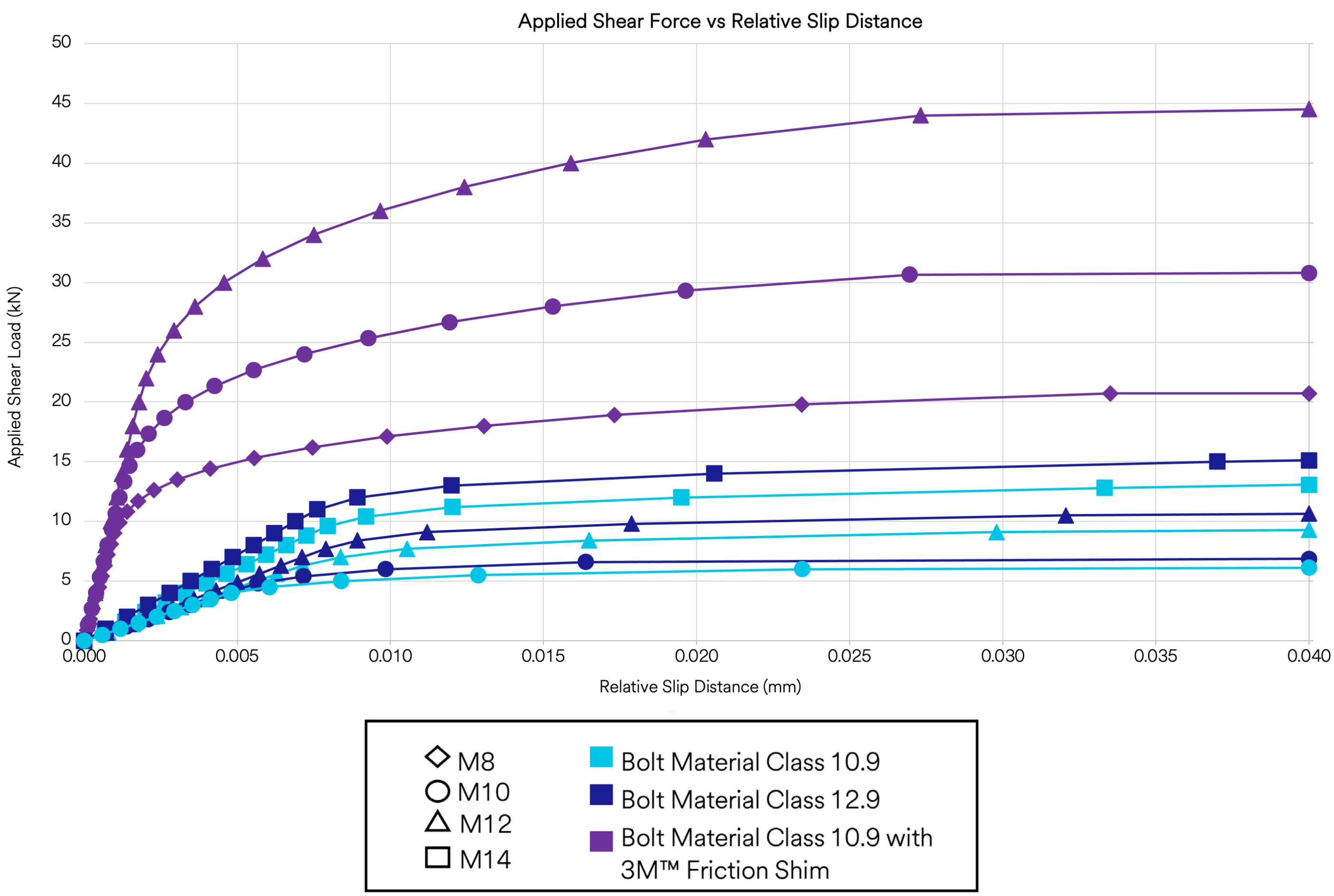

Figure 13: Friction curves detailing how much movement occurs between the two components for given applied force. The point of slippage is defined as 0.020 mm, shown by the dotted line on the graph.

As seen in Figure 14, the modeled force at which the modeled strut slipped relative to the doghouse varied greatly depending on the conditions. By evaluating several different variables separately, the individual effects on the performance of the joint are clear.

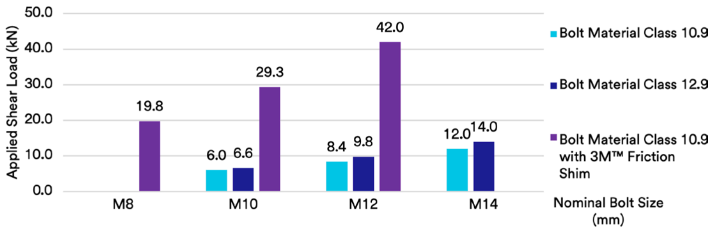

Figure 14: Summary graph of results showing modeled force (kN) when each condition reached a movement of 0.02 mm, defined as the point of slippage.

Note: The modeled force at 0.02 mm of movement was found to be higher than the calculated shear capacity in this finite element analysis study. This potentially occurs due to the elastic behavior of the joint components, such that the shear load is partially carried at the bolt head and nut face. Detailed testing and analysis would be needed to verify the accuracy of these results. Although Finite Element Analysis has become a widely accepted tool for engineering analysis, it cannot be viewed as a substitute for testing and field experience of the actual bolted joint.

Detailed Model Results for M10 Class 10.9 Bolt

The figures to the right show results for joints assembled with M10 Class 10.9 bolts: with a 3M™ Friction Shim (Figure 15); without a 3M™ Friction Shim (Figure 16).

The colored rings represent the contact surfaces on the strut and the doghouse and illustrate the local relative slip displacement. The colors are scaled to illustrate the magnitude and distribution of relative displacement, from no relative displacement (blue) to full slip (red). The color shade results labeled with shear load values correspond to the displacement plot points shown above those results. The displacement values in the plot are the maximum slip distance at that applied shear load.

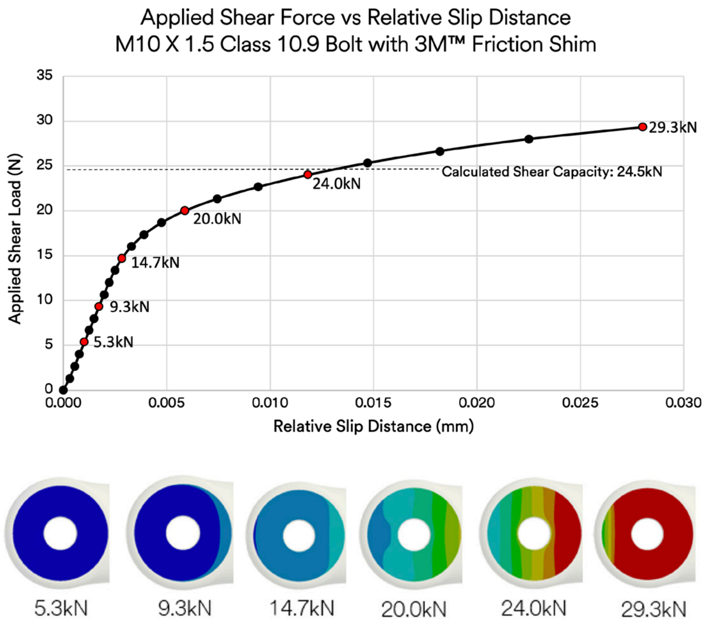

Figure 15: Results for M10 Class 10.9 bolt with 3M™ Friction Shim.

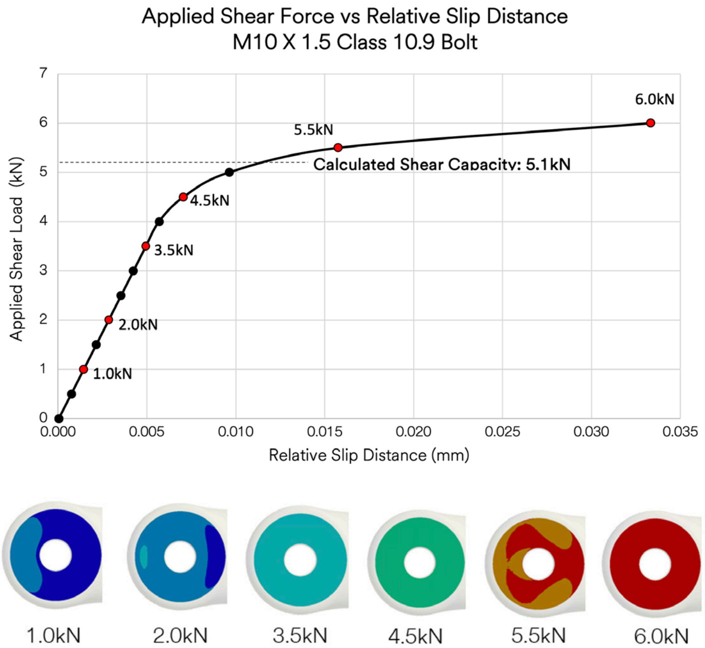

Figure 16: Results for M10 Class 10.9 bolt and no 3M™ Friction Shim.

Discussion

Increased Bolt Size

As expected, increasing bolt size led to an increase in the amount of shear force the joint withstood before slippage. This increase was between 40–49%, with an average increase of 44%.

Percentage increase of force before slippage due to increasing bolt size		
	M10 → M12	M12 → M14
Bolt Material Class 10.9	40%	43%
Bolt Material Class 12.9	49%	43%

Figure 17: Summary table showing the percentage increase for each condition as the bolt size increased one size.

Higher Bolt Material Class

Moving to a higher bolt material class also increased the shear force the joint could withstand before slippage. For the M10 connection, there was a 10.0% increase, while for both M12 and M14 there was a 16.7% increase. The average increase was 15%.

Percentage increase of force before slippage due to higher material class	
Bolt Size	Bolt Material Class 10.9 → 12.9
M10	10%
M12	17%
M14	17%

Figure 18: Summary table showing the percentage increase for each bolt size as the material class changed from 10.9 to 12.9.

Addition of 3M™ Friction Shim

The largest difference was observed when the 3M™ Friction Shim was added to the model. For the M10 connection, there was a 389% increase in the amount of shear force the joint could withstand before slippage; for M12, there was a 400% increase. The average increase was 395%. This significant difference signals a step change in performance due to the added friction between the mating surfaces preventing movement in the connection.

Percentage increase of force before slippage due to 3M™ Friction Shim	
Bolt Size	No Shim → With Friction Shim
M10	389%
M12	400%

Figure 19: Summary table showing the percentage increase for each bolt size due to the addition of a 3M™ Friction Shim.

With a 3M™ Friction Shim, the smallest modeled joint, M8, withstood a higher force (19.8 kN) than the largest modeled joint, M14, with the stronger bolt material class (14.0 kN). Based on the average increase in force enabled by increasing bolt size (44%), an M16 can be expected to withstand forces comparable to an M8 with a 3M™ Friction Shim.

Conclusion

While many factors contribute to the size, number, and placement of bolted connections within a vehicle design, one key factor is the amount of force the joints can withstand before slippage. The FEM model demonstrated that 3M™ Friction Shims, by increasing the coefficient of friction between the mating surfaces, provide a significant step change in the amount of force a joint can withstand. For automotive applications, this can enable more standardization with carry-over designs, as heavier components can be supported without requiring additional design modifications. This friction enhancement method is also proven to be effective on common materials used in vehicle chassis, such as aluminum alloy and e-coated steel.

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