

Influence of Assembly Speed on Electrical Connector Mating Force

Don Price
 USCAR

ABSTRACT

The force required to assemble automotive electrical connectors has been tested using a range of mating speeds in a controlled lab environment. This set of tests answers questions often brought up regarding how mating speed significantly influences the required applied force. Data from these evaluations show small but consistent mate force changes with assembly speed. Sealed and unsealed connectors were found to respond differently to mating speed, which is explained using a theoretical analysis. The mechanical analysis explains what forces are involved and how they are influenced by speed. Practical recommendations are given on how mate force testing should be done to assure results are as useful as possible. Results show that that mating speed has a positive correlation to peak mate force. An opposite, negative, correlation for unsealed connectors was found. Follow-on discussion explains why slow and accurate testing is preferred to testing at the actual speeds seen in the plant. Higher-speed testing is shown to lessen the accuracy of test results based on comparisons of the standard deviations of the slow and fast measurements.

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INTRODUCTION

Each of the 300 (or more) electrical connectors in a vehicle is assembled by hand making assembly ergonomics for connectors important. For more than 20 years, actions have been taken to reject connectors with mating forces high enough to risk injuries to assembly workers. The risk was for a repetitive stress type of injury. To make connector mate force science-based and not subjective, much research was done and the USCAR-25 specification [1] was developed to define exactly what forces are and are not allowed based on ergonomic science. SAE/USCAR-25 has been extremely successful. When the latest revision was released in March, 2016, no changes were made. This indicates the specification is mature regarding connector mating force and the current specification is meeting needs as-written.

Since SAE/USCAR-25 was first released in 2008, many connectors have been designed with good assembly ergonomics as a prime consideration. The SAE/USCAR-25 specification and also the SAE/USCAR-2 specification [2] define 75 N as the maximum mating force (for an optimally-sized connector in a favorable assembly location and less for unfavorable location or posture). Despite the success of the 75 N value, there is one question that keeps coming up related to the speed of testing. Specifically, it is asked frequently why specifications measure mating force at a relatively slow speed even though the assembly worker is known to assemble at a higher speed. This technical paper reports on testing performed at three different speeds and the impact of mating speed.

This paper is organized into three sections: 1) Prediction of speed on connector mating forces based on applied mechanics theory. The theory of connector mating is well understood and this section reviews existing models of speed and force interaction. Existing literature was not available on the contribution of trapped air (compressed inside a sealed connector) to mating force so that analysis is original. 2) Experimental results of actual connector mating evaluations at different speeds. This section includes an analysis of whether the theory and experimental results match and makes conclusions. 3) The paper concludes with a recommendation for future experimental work to advance knowledge on this topic using a different type of load cell.

MECHANICS OF CONNECTOR MATING

In this section, connector theory is used to predict how mating speed influences the required mating force. This allows the experimental results to be compared with the expected (theoretical) results.

Prediction of Mating Speed

There is a theoretical concern mentioned often in connector labs that the lab test methods (speeds) used today do not match the actual use of the part when assembled. In this section, analysis is offered on why the lab tests were designed as they are. The current lab-based test speed is 50mm/min. and this is common to all known connector specifications. This speed is used, for example, in SAE/USCAR-2 that is used extensively in North America. The speed of 50mm/min. is the metric adaption of 2 inches per minute used previously. Historically, the reason given is that this speed is slow enough so mating parts would not bind and be pulled apart artificially interfere with

each other to give inaccurate readings. Informal gauge R&R (repeatability and reproducibility) studies showed that acceptable results can be obtained at this speed but it was unknown how higher speeds would impact repeatability.

Being a manual operation, there is a range of speeds used to mate connectors. For purposes of this research, an exact value is not needed, but an estimate is needed to see how far this speed differs from the lab testing speed. As an approximation, a standard hand-mate connector is taken to travel distance from first blade contact to final stop of 5mm and use the time approximation that the motion takes 250ms. Per Equation 1, this results in a speed of 1200mm/min.

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}} = \frac{5\text{mm}}{0.25\text{s}} = \frac{20\text{mm}}{\text{second}} = \frac{1200\text{mm}}{\text{minute}} \quad (1)$$

This approximated speed is 24 times faster than the lab testing speed of 50mm/min. With the test speed being many times slower than the typical assembly speed in a vehicle assembly plant, it's no surprise it has generated concerns that lab testing is not representative. Although being not the same does not equate to being a problem. As mentioned before, the team updating USCAR-25 to revision 3 (released in 2016) did not change the force requirements, indicating there is not a problem with repetitive stress injury. Only if assembly-related injury was present would a new test method (to test at representative speeds) be sought.

Implementing accurate high-speed testing is difficult for the reason that all high speed testing is at risk: the part alignment is not as good at higher speeds. But there is also a second reason specific to connectors: when the connector hits the bottom of the mating connector, the test operator does not have time to stop the test and may include the much higher "bottomed-out" force data. In the next section, each contributing factor to mate force is reviewed.

Types of Forces in Connector Mating

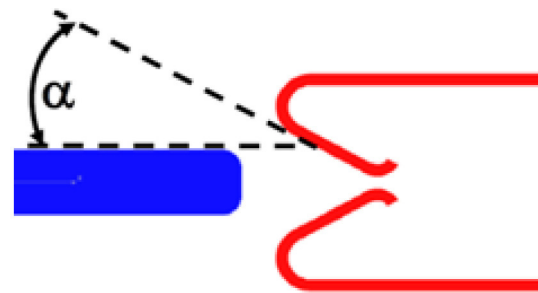
There are several types of forces that contribute to connector mate force; generally they are broken down into forces opposing friction, forces opposing spring-like components, and forces opposing air compression (for sealed connectors). Friction is believed to be a major factor. This is significant since friction is sensitive to speed, unlike other mechanisms. Therefore, understanding the major contributors and their relative contribution is important in predicting whether increased speed should contribute to increased force to mate a connector.

Table 1. Contributions to connector mating force.

	Mechanical Action	Theoretical Relationship -Mating speed to force-
1	Terminal beam deflection (at initial mate)	Force will increase linearly with speed
2	Sliding (terminal, seal, and connector)	Force is independent of speed for sliding
3	Locking beam deflection (near end of mate travel)	Force will increase linearly with speed
4	Compression of air (sealed only)	Force will increase (design dependent).
5	End-of-travel (Deflection of plastic when bottomed-out)	Force is proportional to deflection of housing

Four of the 5 contributions to mating force are predicted to increase as mating speed increases, so a quick assumption may be that the overall force will increase significantly with speed. But the one largest force present when peak force is reached is sliding friction and it stays constant with speed. So, initial assumptions must be rejected and in-depth analysis performed. In the following section, each mechanical action that contributes to mating force is described in detail. Paragraph numbers in the following section match numbers in Table 1.

1. "Terminal beam deflection" is where energy is expended to make the terminal beams spread. This condition has been described in previous papers [4, 5, 7]. This discussion will not further explain mechanics that are already documented. Energy is required to spread the female terminal beams from their resting gap spacing to the engaged connector gap. Since the energy to move the beams is the same, applying this energy in less total time would result in higher power requirement, and therefore mating forces should increase with speed. However, beam spreading is a contributor to mating force only at the start of the mating cycle. Even though the force increases proportionally to the mating speed, it is not seen as a factor in the peak speed. Figure 1 and Equation 2 describe the relationships [5].



Where:

α = entry angle and μ = Friction coefficient

Figure 1. Illustration of terminal mating used in theoretical insertion force calculation per Equation 2, which describes the geometric relationship.

$$F_{\text{Insertion}} = N \cdot F_{\text{Normal}} \left(\frac{\sin \alpha + \mu \cdot \cos \alpha}{\cos \alpha - \mu \cdot \sin \alpha} \right) \quad (2)$$

Where

F = applied force,

μ = Coefficient of Friction

N = Normal force between the sliding surfaces

2. Sliding occurs over the entire length of travel for connector mating. Figure 2 shows an idealized representation of the regions for initial deflection and sliding before locking beam deflection [5].

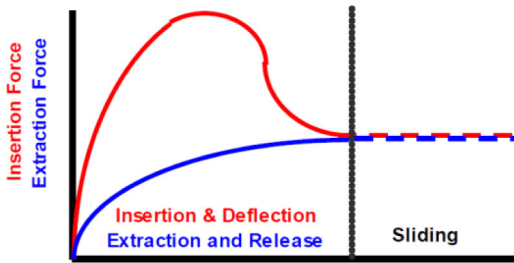


Figure 2. Illustration of “Beam Deflection” (left) and “Sliding” (right) regions per Table 1 items 1 and 2. Sliding region is not influenced by speed, as predicted by Equation 3, since it does not have any terms influenced by speed.

Equation 3 shows the relationship for sliding friction that is commonly accepted to apply to connectors [5]. Sliding friction applies to terminals, seals, and contacting housing parts so its contribution is believed to be large. The important point, again, is that frictional forces do not increase with speed since there is no speed-related factor in Equation 3.

$$F = \mu N \quad (3)$$

Where

F = Applied force,

μ = Coefficient of Friction

N = Normal force between the sliding surfaces

3. Locking beam deflection is similar to contact beam deflection and mating force in this region increases linearly to speed. This region is typically the highest force since the locking force needs to be added to the sliding force. Therefore, this region may have an impact on increasing forces as mate speed increases. However, most modern lock designs require only minimal additional force, making this less significant.
4. Compression of trapped air, which applies to sealed connectors only, should be minimal in a well designed connector but will not be 0. There is no practical way to model the compression since it depends on how and at what mating location the intended design seals. If perfectly vented, there would be no compression and, therefore, no mating force contribution. In a theoretical worst-case situation where a connector is designed with no escape path (where even the wires are sealed) then mate force would increase from both the energy needed to compress the air and the force to oppose the static pressure. Sealed connectors have been measured to have transient pressures of 37kPa (~5.4 psi) when mated at production speed [4]. If the pressurized surface area of a connector is 200mm² then a pressure of 37kPa could increase the mate force by up to 7.4N (0.037 Pa * 200 mm²). The static pressure would be independent of speed. The force (energy) used to pressurize the air would be speed dependent but is expected to be not as significant of a factor since the highest mating force is typically at the end of the travel, just before the connector lock engages and the air would be pressurized by that point. If the mating speed is

relatively slow, pressurized air leaks out of the connector. This likely will explain a difference between fast speeds in sealed and unsealed connectors. Research shows a 20% decay in pressure occurs in the 1st second after high-speed (~1200mm/min.) compression [4] which would mean that lab testing would allow most or all the pressurized air to leak and field assembly would not.

5. The force to “bottom out” (pushing a connector beyond the position where it is fully mated) can be significant. The engagement force increases quickly as parts of the connector are pushed further than intended in the design. In this condition, the connector half being plugged in has hit the “bottom” of the mating part and slightly deflects the stiff plastic connector housing. This condition is easy to detect on a slow-speed (50mm/min.) force-displacement plot by its steep slope at the end of the mating travel-versus-force plot as shown in Figure 3. Bottoming-out is also easy to detect by an assembly operator who can feel the steep rise in force. However, it is not easy to eliminate measurement of some of this force in manual force measuring equipment (often used in the field) since typical field measurements record peak force only. This is believed to be the largest source of error with manual/field test equipment. Bottom-out force is driven by Hooke’s law, shown in Equation 4. It is used typically to describe the force-displacement behavior in springs. In this case, the housing acts like a stiff spring.

$$F = -kX \quad (4)$$

Where: k = the spring rate of the connector housing

X = displacement beyond the connector bottom

In this case, k is the stiffness of a spring as stiff as the connector housing; since the housing is rigid, k values are very high, which explains why the force spikes when a connector bottoms-out as shown in Figure 3.

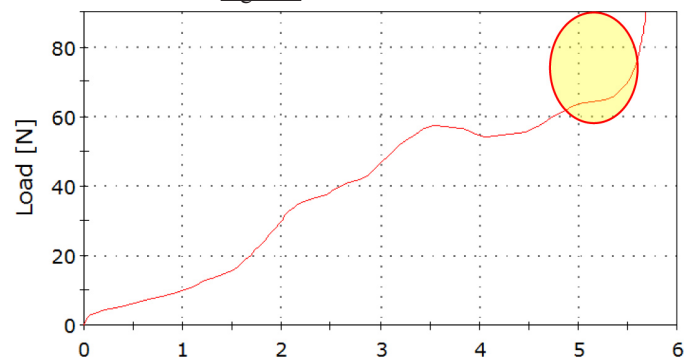


Figure 3. Connector insertion force versus displacement plot showing the steep rise in force typical of the “Bottom-out” region circled [5].

Several successful models have been developed to predict mating forces using the above listed contributions [6, 7].