

AN INVESTIGATION OF THE COMPRESSIVE HOOK INTEGRAL ATTACHMENT FEATURE

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Abstract

Integral attachment features are a growing method of joining plastic parts. Guidelines and equations that can predict the performance of features are needed for more efficient design. A design of experiments approach has been used to generate approximate second-order equations (response surfaces) which can calculate the insertion and retention forces for the compressive hook integral attachment feature. The data for this investigation was generated using finite element methods. The response equations are based on geometric and material properties of the feature and have been compared to supplemental FEM and experimental results. The results show that in the range of the equation, we can predict FEM results within 10% for feature retention. Guidelines for designing features have also been stated. These results can enhance the performance of the compressive hook feature through an improved design.

Introduction

Integral attachment features (snap-fits) are commonly used today in the manufacturing of plastic parts. Integral attachment features can provide benefits to part design by removing tool requirements and reducing the part count [1]. Integral attachment features include any and all design elements at the interface between parts of assembly to enable, assist, or enhance attachment, including snaps, locks, lugs, stops, etc. [2]

The compressive hook integral attachment feature is a type of lock feature. It is similar to the concept of the cantilever hook feature with the fundamental difference in the direction of loading. Under normal service loads, the cantilever hook is designed to carry tensile loads, while the compressive hook is designed to carry compressive loads. Figure 1 contains an example of a typical feature showing how it is loaded during the insertion and retention processes.

Problem

The compressive hook feature is commonly used in thermoplastic automotive electrical connectors. It has been found that the most frequent cause of discontinuity in these electrical connections is terminal push-out/pullout (TPO). The causes for TPO can be attributed to many different design and/or assembly problems: difficult or improper terminal assembly, improper material selection, improper snap-fit design, etc. [3] One way of improving

the feature would be to design it to withstand the retention forces that it would experience for a particular application.

The compression of the feature when in retention results in a complicated, nonlinear response and makes designing the part to specific criteria difficult. Simple hand calculations are no longer sufficient to predict the response of the feature because of this nonlinear performance for insertion and retention.

Objective

Due to the complexity of the response of the compressive hook feature, the objective of this report is to develop a set of guidelines and approximating equations based on the results of a designed experiment. These guidelines and equations can be used to design and to improve the design of the compressive hook integral attachment feature.

Previous Studies

Some previous studies have been conducted to investigate the response of the compressive hook feature. These studies have used theoretical, numerical, and experimental methods to examine the feature. Finite element methods have been used to model the pullout motion of the snap-fit in order to determine the force at which this failure occurs.

In a study by Rousseau, Kolberg, and Hotra [4], finite element methods were employed because of the limitations of simple hand calculations. Compressive hook features were analyzed with finite element methods and corresponding physical parts were tested to compare the results. The results of the two methods showed good correlation, therefore, it was concluded that finite element methods can be used to model performance of the feature.

Two papers report on a study by Hotra, Siedlik, Woods, Kolberg, and Bals [3, 5]. This study also used finite element methods to analyze the compressive hook feature, but two different failure modes were investigated: buckling and shear. Corresponding physical parts were also tested and compared to the predicted failure from the finite element analysis. An accurate correlation was found between the two analysis methods.

The final paper by Roy [6] was a more analytical study into the statics and dynamics of the compressive hook feature. Two closed form equations were derived to calculate the deflection of the feature during assembly: one for a feature with a variable thickness, and one for a feature with a variable width. Features with a variable thickness are to be investigated in this study.

In order to analytically calculate the column load in retention, the feature is modeled as a tapered beam with a load applied at the center of the top cross-section. Roy uses a Rayleigh-Ritz method to approximate the column load equation.

The equation presented in the study by Roy did not take into consideration the offset location of the load that is experienced by the compressive hook feature. This eccentricity causes a moment on the end of the column which reduces its stability, reducing the load-carrying capability of the fastener. Timoshenko derives an equation for the critical stress in an eccentrically-loaded column of a constant cross-section [7]. This formula, though, does not take into consideration the variable width of the column.

The compressive hook feature has specific attributes that are referred to in this study (see Figure 2). These aspects were modeled similar to previous studies [3, 4, 5, 6]. The beam has a specific length (vertical dimension as shown), width (horizontal dimension as shown), and depth (into the page). The beam is commonly tapered from the tip to the basepart. The retention shelf is the protruding portion that comes into contact with the terminal (retention block). The shelf also has a length, width and depth. The retention face of the shelf is angled approximately 87.5° (back angle) to help prevent the terminal from sliding off the shelf. The retention block (terminal) is shown above the feature for clarity, but is seated on the shelf when assembled. The basepart is the local region of the entire connector from which the feature protrudes.

Research Approach

Overview of Approach

It was desired to obtain a set of equations that can predict the insertion and retention responses of the compressive hook feature and use these equations to develop guidelines to assist in design. These equations use the geometric properties of the feature to calculate the expected insertion and retention forces.

A designed experiment is an appropriate tool in order to efficiently obtain the necessary information. The designed experiment arranges the levels of the factors so that an appropriate equation can be fit to the data using regression analysis. A finite element analysis was conducted on each feature design in the study in order to get the necessary information to fit the equations. Tests with physical parts were then used to confirm the finite element results and the design equations. Guidelines to design the feature were formed from the equations by examining the trends in the response of the feature due to changes in the inputs.

Response Surface Generation

In order to define the response generated by varying the design factors to an acceptable level of accuracy, a second-order response surface was desired. An experiment designed to fit this type of model can be used to produce a second-order equation without having to use a large

number of experimental runs. A response surface model is constructed from a two-level factorial design with additional sample points at the center and at two extreme ends of each axis (axial points). Each axis represents one of the design factors.

Design of Experiment

From an initial finite element investigation of the feature, it was found that the important factors which should be included in this study were beam length, beam width, offset, shelf length, engagement location, and coefficient of friction (see Figure 3). The engagement location was only considered as a design variable in the retention analysis in order to determine how the feature performs when not assembled properly. Full engagement was used for the insertion analysis. Because there is minimal sliding during retention, the friction coefficient was not found to be a significant variable, but it was included for the insertion analysis. The width of the retention block was chosen to match current designs where this feature is being implemented. Table 1 gives the range of values for each factor used in this experiment. Following a method for determining appropriate factor levels as described by Montgomery [8], the numerical values of the axial points used in this experiment were these high and low values. The values for the center and factorial points can be calculated from these high and low values with the center being the average value and the factorial points falling half way between the high and center points or low and center points.

Data Collection - Finite Element Results

Finite element methods were used to model the compressive hook feature as it is subjected to insertion and retention processes. The features were modeled and the reaction forces found using the same methods as outlined by Luscher [9]. The material model used in the analysis was for acrylic butadiene styrene (ABS) as an elastic/perfect plastic material with an elastic modulus of 2.24 GPa and a Von-Mises yield criteria of 41.4 MPa. To simulate the assembly and disassembly processes, a fixed displacement condition was applied to the bottom and right edge of the basepart so that the feature comes into contact with the rigid retention block which is held fixed. It was assumed that a plane stress condition exists while the feature is loaded.

In order to achieve an acceptable level of accuracy, the non-linear finite element software package, ABAQUS, was used for this analysis. With non-linear capabilities, this solver is capable of modeling the snap-through during insertion as well as potential buckling of the beam under retention.

The reaction forces needed to displace the features as determined through finite element methods were recorded for each case. These calculated force values can be plotted versus the position as shown in Figure 4. The maximum force value during the assembly process will be called the insertion force [2], and an average maximum force value during the disassembly process will be called the retention

force. This retention force was calculated by averaging the forces over a displacement range of ± 0.125 mm around the maximum retention force (Figure 5). This was done to filter out any noise that might occur in the finite element analysis as it tries to converge on a solution. This measurement represents the force necessary to cause failure in the feature either by buckling of the beam or by material failure in the retention shelf. Because a designer might be interested in the amount of force that a feature might hold before permanent deformation begins to take place, a third force measurement was recorded and named the proportional limit. For this study, this point was chosen to be where the force value deviates from the linear region at the beginning of the force-displacement plot by over 10% (Figure 5).

Data Collection - Experimental Testing

Verification of the finite element models was performed using ABS injection molded test samples which were molded using a Battenfeld BA200CD injection molding machine. The geometry of the samples was similar to that used in the finite element analysis with the exception that the basepart was not included. Instead, the beam was molded longer than necessary to allow the sample to be gripped in the test fixture. This provided a slightly different end condition than in the finite element analysis.

The expected retention forces lead to the use of a solid block of aluminum for the retention block. This was due to the fact that any fixturing designed to simulate the rigid retention block as modeled in the finite element analysis would most likely fail under the given range of retention forces. The retention block was modified since the goal of the experiments was to measure the strength and response of the compressive hook itself and not its retention block. Insertion tests were performed similarly to retention tests however the mating surface used was the edge of a piece of 0.040" sheet metal.

An Instron 1331 multipurpose testing machine was used to test the parts in insertion and retention. A 1 kN load cell was used to obtain load readings during the test. A personal computer equipped with a National Instruments data acquisition board and LabView software was used to acquire data during all testing. All tests were run at a crosshead rate of 1 mm/min.

Before each test, a sample feature was properly aligned under the retention block in the test fixture. Figure 6 shows the configuration of the device we used to perform the test. During each test, the crosshead displacement and the vertical load were measured and recorded. Each feature geometry was tested several times with each test being performed on a new test sample.

Discussions

Design Equations

Regression analysis of the finite element results for each type of response provided three second-order equations based on the factors used in the experiment. A second-

order equation for five factors can contain up to 21 terms. In order to make the equation easier to use and provide a better fit to the data, only the terms that were statistically significant were included. Statistical analysis software which provided this capability was used to determine the coefficients of each term and calculated which terms had a significant influence on the final response surface. The factors with a p-value greater than 10% were not included in the insertion and retention force models. The calculated coefficients are then used in the final equations (1 - 3).

$$IF = -2.29 + 0.063A + 16.8B - 16.7C + 6.19D - 42.3F + 0.86A^2 + 9.35B^2 - 6.19AB - 2.15AC - 6.55AF + 21.4BC - 7.43BD + 39.9BF + 31.7CF \quad (1)$$

$$RF = 372 - 7.47A + 111B - 333C - 14.4D - 112E + 109C^2 + 147E^2 - 7.84AB + 21.1AE + 25.6BD - 94.1BE - 38.2DE \quad (2)$$

$$PL = -36.6 - 1.64A + 167B - 45.2C + 33.2D - 74.9E - 0.990A^2 - 36.4B^2 + 4.80AB + 5.63AC - 7.24AE - 14.8BD + 37.1BE \quad (3)$$

where IF is the predicted insertion force in Newtons, RF is the predicted retention force in Newtons, PL is the predicted proportional limit in Newtons, A is the length of the beam between 10.2 and 2.5 mm, B is the width of the beam between 2.5 and 1 mm, C is the offset between 2 and 1 mm, D is the length of the shelf between 5.1 and 2.5 mm, E is the engagement between 0 and 0.80, and F is the coefficient of friction between 0.12 and 0.60.

Equation Confirmation

In order to determine the adequacy of the design equations, feature designs which were not in the original experimental matrix were analyzed using both finite element methods and physical testing. The insertion force and retention force were recorded for each confirmation run and compared to the value predicted by the equations (Table 2). All of the insertion forces from the finite element analyses were within 2.5 N of the equation values. The calculated retention forces were within 8% of the finite element solutions. Finally, all of the predicted proportional limit results fell within 7% of the finite element values. Due to the differences in the boundary conditions, the experimental results were not as close to the predicted values as the finite element results.

For the cases that buckled in the finite element analysis, the retention force equation (2) can be compared to the theoretical equations presented by Roy (tapered column) and Timoshenko (secant formula). It can be seen in Figure 6 that neither formula provides a close approximation of the failure load, but many of the force values are off by over 60% compared to the finite element result. These approximations should not be used to predict the buckling failure for this feature. The retention force equation gave the closest approximation to the buckling load for the equations investigated in this study.

Conclusions

Prototyping and physical testing of integral fasteners is a poor and expensive method of designing features. Finite element analysis is also a time-consuming and complicated method. Equations that can predict the performance of a feature are needed for design. An approach has been presented that will generate insertion and retention response surfaces (second-order equations) for the significant design factors of the compressive hook integral attachment feature based on non-linear finite-element results. These equations can be used to estimate the maximum insertion and retention forces for given values of the design variables, or to optimize the design of the fastener according to some retention or insertion criteria. The equations also produce results that are comparable to experimental results.

A design-of-experiment method called level average analysis was used to reveal trends in the response of the fastener that were used to develop guidelines for designing the feature. In most cases, the designer will be interested in two goals, to lower the insertion force and to increase the retention force. It was found that the shelf length should be longer for both goals with the shelf width at a low level (thinner) for lower insertion forces. The friction should be kept at a low level to reduce the insertion force, while the engagement should also be at a low level, close to full engagement, to improve the retention capabilities. Finally, a trade-off occurs when choosing the beam width and height levels. A high aspect ratio (L/W) is desired to lower the insertion force, but that will cause the feature to buckle at lower retention forces. The design equations can be used to determine how much of an effect a certain aspect ratio will have on the feature. These guidelines are summarized in Table 3.

Acknowledgments

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Illustrations

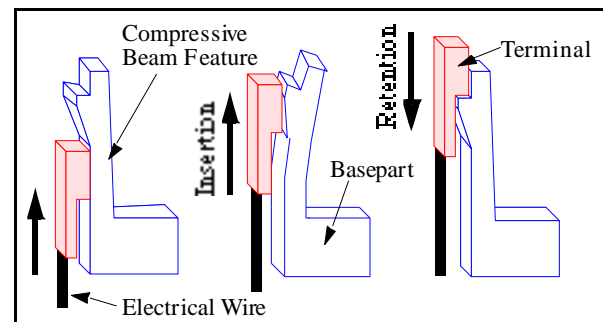


Figure 1. Insertion and Retention Processes for Compressive Hook Feature.

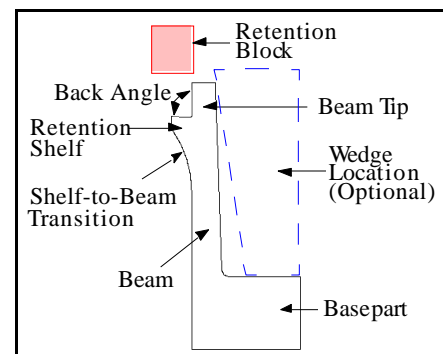


Figure 2. Compressive Hook Nomenclature.

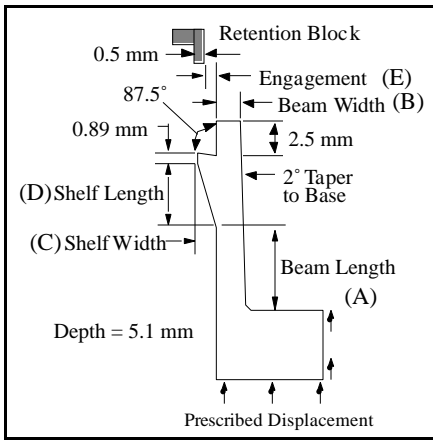


Figure 3. Compressive Hook Feature.

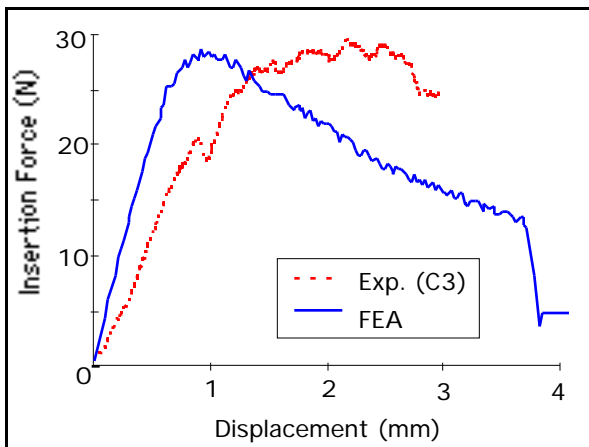


Figure 4. Insertion Force Plot (Conf_C).

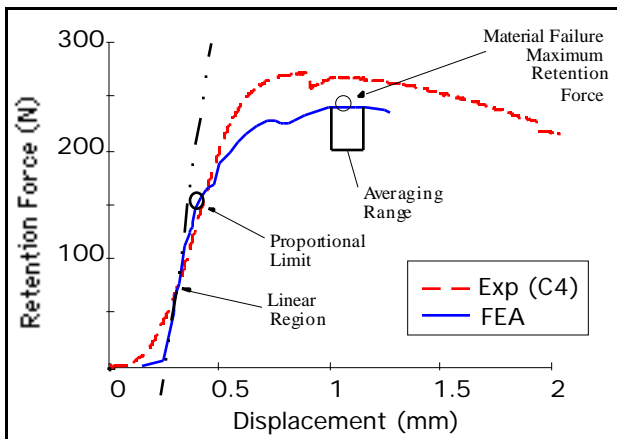


Figure 5. Retention Force Plot (Conf_C).

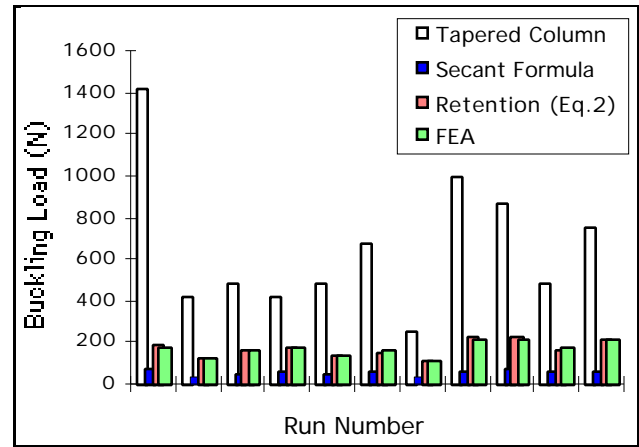


Figure 6. Buckling Failure Load Comparison.

Table 1. Factor High and Low Values.

Level	Beam Length A	Beam Width B	Offset C
High	10.2 mm	2.5 mm	2.0 mm
Low	2.5 mm	1.0 mm	1.0 mm
Level	Shelf Length D	Engagement E (Ret)	Friction F (Ins)
High	5.1 mm	0.08 * C	0.60
Low	2.5 mm	0.0 * C	0.12

Table 2. Confirmation Run Data (N).

	Conf_A	Conf_C	Conf_D
Equation-Ins. (1)	8.11	21.39	10.30
FEA-Ins.	5.44 (33%)	21.01 (2%)	9.96 (3%)
Experiment-Ins.	7.47 (8%)	29.64 (39%)	6.13 (40%)
Equation-Ret. (2)	164.4	218.5	236.0
FEA-Ret.	176.8 (8%)	218.8 (0.1%)	229.5 (3%)
Experiment-Ret.	212.9 (29%)	266.9 (22%)	238.8 (1%)
Equation-Prop. Limit (3)	124.7	121.3	147.4
FEA-Prop. Limit.	118.9 (5%)	122.0 (0.5%)	136.9 (7%)

Table 3. Summary of Design Guidelines.

Factor	Low Insertion	High Retention
Beam Length (A)	Longer	Shorter
Beam Width (B)	Thinner	Thicker
Shelf Width (C)	Thinner	-
Shelf Length (D)	Longer	Longer
Engagement (E)	-	Full Engagement
Friction (F)	Low	-

Key Word Index

Integral attachment, snap-fit, compressive hook feature.