A FINITE ELEMENT INVESTIGATION OF THE BAYONET-AND-FINGER 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 with 2-D and 3-D finite element methods was used to generate approximate linear response surfaces based on feature geometry which can calculate the insertion and retention forces for the bayonet-and-finger integral attachment feature. The results show that in the range of the equation, we can predict FEM results within 23% for feature retention. Guidelines for designing features have also been stated. These results can be used to enhance the performance of the bayonet-and-finger 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 bayonet-and-finger style snap-fit is one design that can be used as the attachment between a part and a thin wall or basepart. The bayonet is a cantilever-style hook on the part that retains the attachment with a combination of an axial force and bending moment. The end of the bayonet with an offset catch is inserted through an opening in the basepart. On the bottom of the basepart, fingers provide a locking mechanism to keep parts attached. Figure 1 shows the two mating parts before insertion. The retention finger is a beam that, along with the bayonet, takes retention loads as axial forces and bending moments. The angle it makes with the basepart frame is the retention angle. The support finger is molded onto the basepart opposite to the retention finger. It provides support to the bayonet by limiting the amount of bending during retention, and ensures full engagement of the offset before retention. The angle it makes to the basepart is called the support angle.

As the bayonet is inserted, the fingers have to flex away to allow it to pass until the offset clears the end of the finger causing it to snap into place. The snap-fit will then take retention loads, and prevent parts from coming apart unless failure occurs. A study of the failure of the bayonet-and-finger snap-fit was conducted by Wang [3]. It was found that the retention finger buckles and the bayonet and support finger both bend at the same rate. Some material yielding also occurs at the offset.

Problem

The reaction 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. This results in difficulty in designing the feature in order to withstand the retention forces that it would experience for a particular application.

Objective

Due to the complexity of the response of the bayonet-and finger feature, the objective of this report is to investigate the effect of geometric dimensions on the response of the feature in order to develop a set of guidelines and approximating equations. These guidelines and equations can be used to design and to improve the design of the bayonet-and-finger integral attachment feature.

Research Approach

It was desired to determine the effect of the geometric properties of the feature on its performance. This information can be used to obtain design guidelines and a set of equations that can predict the response of the bayonet-and-finger feature. A designed experiment is an appropriate tool in order to efficiently obtain the necessary information.

Once the data had been collected, statistical methods were used to generate the guidelines and equations for the responses. Regression analysis was used to determine the curves of best fit.

Design of Experiment

Five dimensions were chosen as the significant design factors for the investigation: the angle of the support finger, the angle of the retention finger, the vertical length of the fingers, the base thickness of the bayonet, and the size of the offset. These factors, labeled in Figure 2, focus on the catch geometry since this feature is assumed to have a great effect on the snap-fit performance.

A test using two levels for each factor was considered sufficient for the study. The dimensions of the snap-fit were varied between selected high and low values given in Table 1 which cover a large portion of the design space. A typical orthogonal array was used to design a two-level, five-factor experiment following a method as described by Montgomery [5]. This fractional factorial design considers high-order interactions as negligible, and can only consider interactions between two factors. A total of sixteen different trial geometries are necessary for this study.

Analysis - 2-D Finite Element

Finite element methods were used to model the bayonet-and-finger feature as it is subjected to insertion and retention processes. In the previous study by Wang [3], two-dimensional (2-D) finite element analysis (FEA) results were compared to experimental results found by testing a physical part. An accurate correlation was found between the two methods, therefore, FEA is an acceptable method for conducting this study.

The features were modeled and the reaction forces found using the same methods as outlined by Luscher [4]. Four-node rectangular elements and contact surface elements were used with an adequate amount of mesh refinement throughout the model. High mesh concentrations were required on the sliding contact surfaces. A 2-D example of a meshed feature is given in Figure 3.

The basepart had vertical and horizontal constraints at the extreme ends, allowing flexibility at the area where the fingers are attached. The end condition at the base of the bayonet was a prescribed vertical displacement, but it was allowed to float in the horizontal direction. It was assumed that these boundary conditions accurately represented typical loading and support conditions on the feature. It was also assumed that a plane stress condition occurs under loading.

The material model used in the analysis was based on high-impact polystyrene (HIPS). It was modeled as an elastic/perfect plastic material with an elastic (Young’s) modulus of 1.76 GPa and a Von-Mises yield stress criteria of 24 MPa. A friction coefficient of 0.20 was used on the contact surfaces.

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 of the bayonet during insertion as well as potential buckling of the finger under retention.

The reaction forces needed to displace the features were recorded for each case. The maximum force value during the assembly process will be called the insertion force, and the maximum force value during the disassembly process will be called the retention force. The retention measurement represents the force necessary to cause failure in the feature either by buckling of the finger or by material failure in the bayonet offset.

Analysis - 3-D Finite Element

Following the 2-D analysis, it was decided to conduct a three-dimensional (3-D) investigation. This time, the parametric trial geometries of the bayonet-and-finger feature were modeled and meshed using PROSTAR™.. Eight-node brick elements were applied with reasonable mesh refinement throughout the whole model. An example of a 3-D model while under retention loading is given in Figure 4.

Subsequent finite element solving was performed using ANSYS™. The sliding contact of the bayonet and fingers is simulated by using the ANSYS 3D surface contact element - CONTAC49. An elastic Coulomb friction assumption was used in the model. Again, an elastic-perfect plastic model with von-Mises criterion was used to describe the behavior of HIPS.

For the 3-D models, the outer rim of the basepart was constrained in three directions. The fingers were attached to the basepart on two sides of a rectangular hole (penetration) through the basepart. This changed the flexibility of the area where the fingers are attached. Also, the base condition of the bayonet was modified to prohibit horizontal motion.

Only the retention analysis was conducted with the 3-D models. The reaction forces needed to displace the features were recorded for each case to determine the maximum retention forces. Also, the maximum length of the finger for the analysis was shortened to 12.7 mm.

Discussions

The force necessary to displace the bayonet was plotted versus distance as shown in an example of insertion in Figure 5. This reaction force begins (Point 1 in Figure 5) as just the force due to the friction of the bayonet as it slides down the first finger it comes in contact with. Once the bayonet meets both fingers, it starts bending them apart in order to pass through which is seen as a rise in the insertion force (Point 2). A little disturbance occurs in the data (Point 3) at the point where the tip of the bayonet clears the support finger. The force continues to rise as the bayonet pushes the fingers apart in order to allow the offset to pass. There is a dramatic decrease in the reaction force (Point 4) when the offset clears the retention finger. The noise in the rest of the data (Point 5) is from convergence problems in the solution as the bayonet slides past the fingers as parallel surfaces. The software converges better when the contact forces are perpendicular rather than parallel.

An example of a retention run can be found in Figure 6. The bayonet was started from the fully inserted position and then pulled out of the part. When the offset came into contact with the end of the retention finger, the force began to increase (Figure 6 Point 1) from the compression in the retention finger. At a certain point, the retention finger begins to buckle, which causes the retention force to decrease (Point 2). Following this, the bayonet passes by the tip of the support finger causing the force to drop quickly (Point 3). The force continues to decrease (Point 4) as failure of the retention finger continues.

Some of the maximum retention forces obtained by 3D finite element analysis are lower than those found in the 2D analysis. This could be attributed to two different factors. The first is the 2D finite element analysis used the plane stress assumption which might have over predicted the stiffness of the base part, the bayonet and the fingers. The 3D model which takes the base part geometry into consideration provides a better understanding of the overall structure performance during retention process. Second, it was found that for some of the models with conflicting retention forces, the different constraints applied to the base of the bayonet contributed to the difference.

A design-of-experiment method called level average analysis [5] was used to reveal trends in the response of the fastener in order to develop guidelines for designing the feature. The level average analysis information can be plotted to show the significance of each factor in insertion (Figure 7) and in retention (Figure 8 for the 2-D analysis and Figure 9 for 3-D). The factors with a positive slope cause a higher response at level two, while the ones with a negative slope decrease the force at level two. For example, a higher insertion force occurs at the shorter finger length. The magnitude of the sensitivity of the responses to changes in the design factors is the difference in the average response between the two levels, i.e. the insertion force increased an average of 1.25 pounds by increasing the offset to the higher level. The interaction between the factors can also be investigated in a similar manner.

In the insertion analysis, the finger length is the most significant factor, and the other factors all have about the same amount of effect on the response. Differences occur between the results from the analysis of the 2-D and 3-D data. As can be seen, the finger length had the largest effect on retention, but the two methods had different sensitivities to the change in levels. For the 2-D method, the support angle was the next most significant factor, while the retention angle was more important for the 3-D analysis. The other three factors have almost same lever effect on the system for both analyses. Finally, the 3D model predicted a positive effect to the bayonet thickness on the maximum retention force which is different with 2D analysis results.

Design Guidelines

In most cases, the designer will be interested in two goals, to lower the insertion force and to increase the retention force. The level average analysis results were used to determine which levels of the factors achieved these goals. For this feature, most of the guidelines for one goal interfere with the guidelines for the other goal. A trade-off has to occur to optimize the design of the bayonet-and-finger feature. These guidelines are summarized in Table 2. The difference in the effect of the bayonet thickness between the two modeling methods resulted in a conflicting guideline for this factor.

Design Equations

Regression analysis of the data provided three equations (1 - 3) based on the factors used in the studies. Statistical analysis software which provided this capability was used to determine the coefficients of each term.

$$IF = 33.2 - 0.169A - 0.096B - 1.65C + 9.75D + 8.72E \qquad (1)$$

$$RF_{2\text{D}} = 1140 - 3.85A - 1.33B - 16.2C - 101D + 98.8E \qquad (2)$$

$$RF_{3\text{D}} = 365 - 0.892A - 1.15B - 13.1C + 38.0D + 29.8E \qquad (3)$$

where IF is the predicted insertion force in Newtons,
$RF_{2\text{D}}$ is the predicted retention force from the 2-D analysis in Newtons,
$RF_{3\text{D}}$ is the predicted retention force from the 3-D analysis in Newtons,
A is the support angle between 110° and 135°,
B is the retention angle between 90° and 135°,
C is the finger length between 6.35 and 19.05 mm,
D is the bayonet thickness between 2.03 and 2.54 mm, and
E is the size of the offset between 0.64 and 1.27 mm.

Equation Confirmation

In order to determine the adequacy of the design equations, a feature design which was not in the original experimental matrix was analyzed using 2-D finite element methods (Table 3). The insertion force and retention force were recorded for this confirmation run and compared to the value predicted by the equations. Equation 1 predicted an insertion force of 15.9 Newtons, and the FEA found the force to be 4.6 N. The retention equation predicted a force of 311 N, while the FEA resulted in a force of 240 N, a 23% error.

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. Guidelines and equations that can predict the performance of a feature are needed for routine design. An approach has been presented that will generate insertion and retention response surfaces (linear equations) for the significant design factors of the bayonet-and-finger 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.

Linear regression analysis of the results produced these initial design equations. These equations are linear approximations of what is likely a non-linear response. This can be seen in the confirmation finite element run using the mid-range value for the finger length which resulted in forces that were slightly lower than expected. The equations over-estimated the response in the middle of the investigated range.

Future research includes obtaining higher order equations which can predict the non-linear response of the feature, and testing of physical parts to determine the proper boundary conditions and the adequacy of the 2-D modeling.

Acknowledgments

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5. Montgomery, D., 1991, *Design and Analysis of Experiments, 3rd Edition*, John Wiley & Sons, New York.

Illustrations

Figure 1. Bayonet-and-Finger Snap Fit.

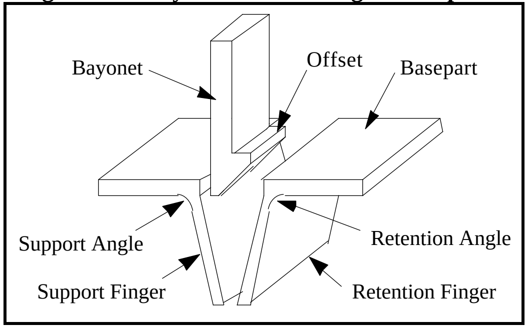

Figure 2. Significant Design Factors.

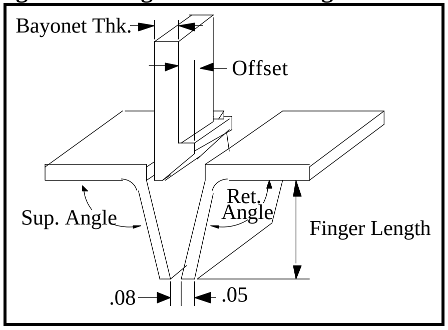

Figure 3. Example of 2-D Meshed Model.

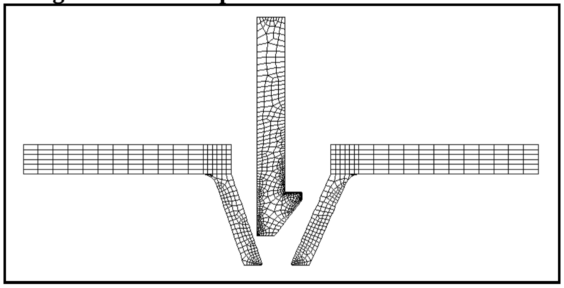

Figure 4. Example of 3-D Meshed Model

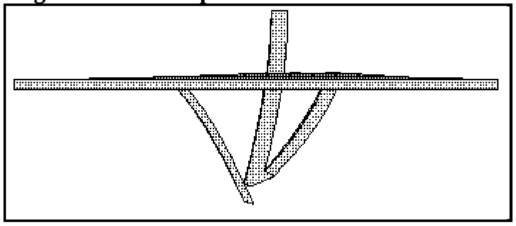

Figure 5. Insertion Force Plot (run #8), with key points shown.

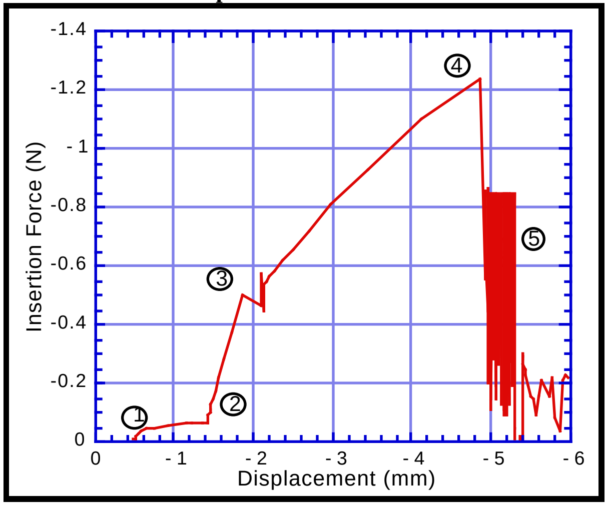

Figure 6. Retention Force Plot(run #14), with key points shown.

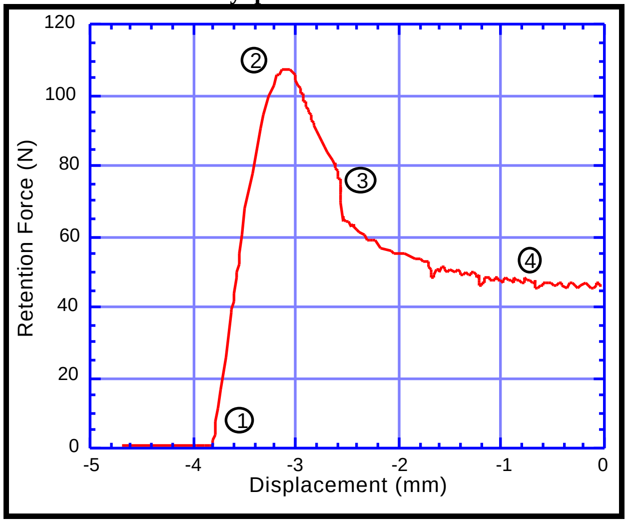

Figure 7. Insertion Force Main Effects.

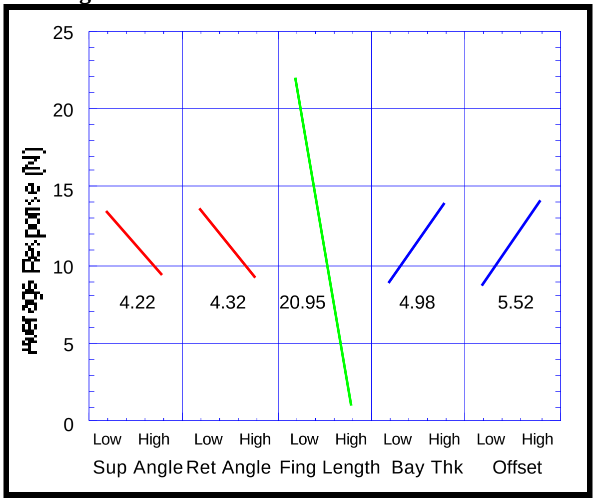

Figure 8. 2-D Retention Force Main Effects.

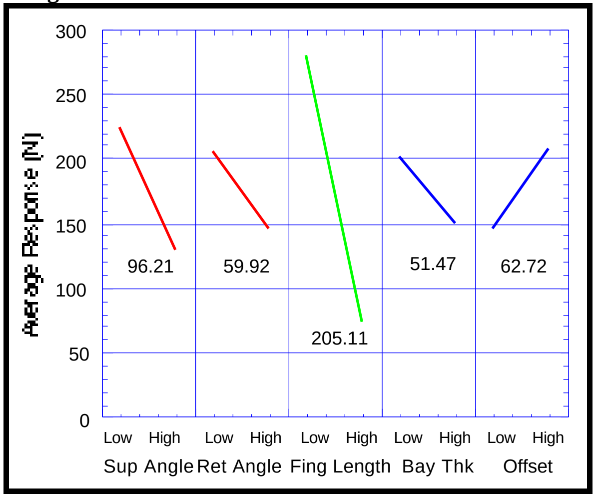

Figure 9. 3-D Retention Force Main Effects.

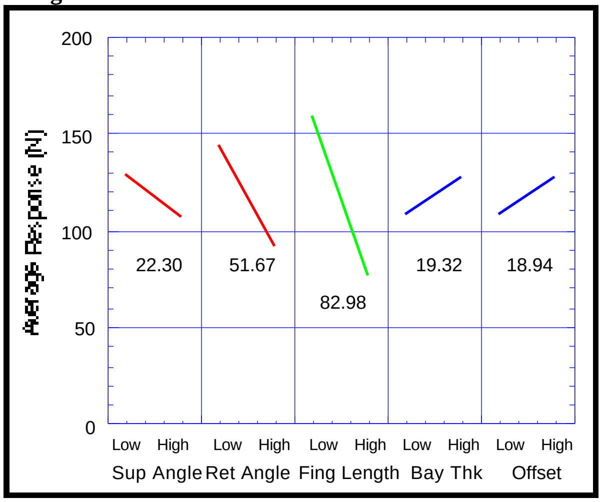

Table 1. Factor High and Low Values.

Level	Support Angle	Retention Angle	Finger Length	Bayonet Thk.	Offset
High	135°	135°	19.05 mm	2.54 mm	1.27 mm
Low	110°	90°	6.35 mm	2.03 mm	0.64 mm

Table 2. Summary of Design Guidelines.

Factor	Low Insertion	High Retention
Support Angle	Larger	Smaller
Retention Angle	Larger	Smaller
Finger Length	Longer	Shorter
Bayonet Thickness	Thinner	Thinner (2-D) Thicker (3-D)
Offset	Smaller	Larger

Table 3. Confirmation Run Geometry.

Support Angle	Retention Angle	Finger Length	Bayonet Thk.	Offset
110°	90°	12.7 mm	2.03 mm	1.27 mm

Key Word Index

Integral attachment, snap-fit, bayonet-and-finger feature.