The Mechanics and Optimization of Cantilever Snap Joints

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Abstract

Market pressures of a world economy demand that corporations continually develop more efficient and cost effective product designs in a shorter period of time. Prior to the development of modern age plastics and molding techniques, components for products had to be fabricated from expensive casting and or machining processes. Once fabricated, multiple component assemblies were secured together using numerous fasteners or rivets. Plastic molding technology combined with innovative snap joint designs now allows for complex net shape parts to be fabricated and snapped together cost effectively.

The design of plastic components utilizing snap fits that are easy to snap together, provide a secure joint, and don't break when snapped together, presents a major challenge for the product design engineers. Since mold die tooling represents a major capital investment with long lead times, the snap joint designed must work right the first time with minor tooling modifications. Classical analysis of snap joints utilizing beam formulas are often only crude approximations and usually do not address the secureness or holding strength of the snap joint. Non-linear contact analysis capabilities found in finite element analysis programs like ANSYS, combined with fast personal computers, now allow engineers to rapidly evaluate and optimize snap joint designs prior to committing to costly prototypes and tooling.

Presented is the non-linear contact analysis of a tapered cantilevered snap joint commonly used to join multiple plastic molded components. Primary focus of this investigation is the optimization of joint secureness as influenced by snap engagement, rake angle, coefficient of friction, material modulus, and cantilever taper ratio. Snap joint mechanics and snap joint cam-out phenomenon during pullout are discussed in detail.

Technologies like finite element analysis play an important role in allowing product design engineers to develop and optimize robust snap joint designs up front prior to fabricating costly mold die tooling.

Nomenclature

E - Snap fit material modulus of elasticity

ϵ_i -Point at which to evaluate integral for Gauss-Legendre Quadrature

H_i - Weighting factor for Gauss-Legendre Quadrature

I (x) - Snap section second moment of area as a function of x.

K - Lateral stiffness of cantilever snap beam at the snap catch

L - Length of snap beam.

M (x) - Bending moment as a function of x

P - Lateral load on snap at installation

t (x) - Snap thickness as a function of x

t_t – Thickness of snap beam at catch

t_b – Thickness of snap beam at base or root

R – Snap beam taper ratio

w – Width of depth of snap into the paper

x – Arbitrary position along the snap beam

δ – Deflection of snap at the catch location σ – Maximum nominal bending stress at root or base of snap beam

Introduction

Virtually all consumer and industrial products, utilizing plastic molded components, have multiple components attached together with some form of snap fits. This utilization of snap fit joints for plastic molded components provides an easy and cost effective method to attach multiple component assemblies. Snap fit joints are made possible because of the inherent flexibility and toughness of modern thermal plastics. Thermal plastics used in products are typically 30 to 100 times more flexible than metals like steel or aluminum. The stiffness of the thermal plastic can be altered by adding glass fibers or composites to the base resin. Since mold die tooling represents a major capital investment with long lead times, getting a snap joint design right the first time presents a major challenge for the design engineer. The snap joint must be designed not fracture or take a set when first snapped together, must securely hold the mating parts together, and be somewhat easy to snap together in production. A straight or tapered cantilever beam with a lead-in ramp and snap catch surface is one of the most commonly used snap fit designs by engineers. Historically the analysis of these cantilever snap fit designs has been limited to using classical beam formulas to calculate lateral stiffness and nominal stress levels at the root of the snap. Most of the focus has been on making sure that the snap doesn't break or fracture upon initial insertion. Equally important to snap failure, is the secureness of the snap joint when subjected to loads by the end user or shock and vibration environments found in industrial applications. The main reason you don't see much information in publications about snap joint secureness is because it is difficult to calculate using classical analysis with simple beam formulas. For this reason the author selected this as a topic for investigation by utilizing the non-linear contact analysis capabilities with in a finite element program like ANSYS to simulate the Cam-out or secureness of a cantilever snap joint.

Cantilever Snap Joint Design Considerations

The design of a cantilever snap joint encompasses several design considerations such as material selection, ease of installation, installation without fracture, fatigue life for repeated use, and snap joint secureness. Historically snap joint design has been primarily focused on maximizing snap lateral stiffness such failure upon installation does not occur. Analysis methods typically used to design snap fits have been limited to straight cantilever beam formulas from basic strength of materials. This simplified analysis approach doesn't consider snap support stiffness and is limited to calculating the snap beam lateral stiffness and nominal bending stress at the root of the snap.

These traditional snap fit analysis approaches are only first order approximations and don't address another critical aspect of snap design, which is snap joint secureness. We all at some point may have had to tape on a battery cover for a VCR remote or a kids toy, because of a poorly designed snap joint. In many industrial applications where components are subjected to severe shock and vibration environments, assuring that snapped together components remain secure is of major importance. Some factors influencing snap joint secureness are, snap beam lateral stiffness, snap support stiffness, length of snap catch, rake angle of snap catch, snap taper ratio, type of material and coefficient of friction between the snap catch and mating surface.

Two of the most important factors influencing snap joint secureness are lateral stiffness and snap catch rake angle. Lateral stiffness of a snap joint is influenced by both the cantilever beam flexibility as well as the flexibility of the material to which it is attached. In some cases the surrounding structure to which the snap fit is attached may be more flexible than the snap joint itself. Snap fit support flexibility is sometimes referred to as support stiffness. In the late 1980's, Allied Signal Plastics published a Snap-Fit Design Guide which documents the influence of support stiffness based on a deflection magnification Q factor. This Q factor is presented in the form of several graphs for various generic snap-fit support situations and is based on detailed finite element studies conducted.

The rake angle of a snap joint catch is another critical design factor influencing joint secureness. For situations where a part must be easily removed, a positive catch rake angle may be implemented. A positive rake angle provides a lateral load component on the snap beam which allows it to cam out more easily when loaded. Tool makers prefer snaps with positive rake angles because ejection of parts and fabrication of the tool are made much easier. Contrarily, snap fits utilizing negative rake angles require more complex die tooling but have significantly higher pull strengths. Snap fits with negative rake angle catches are analogous to barbs on an arrow head or fish hook. Close examination of standard telephone handset cords reveals a snap fit with a negative rake angle to improve cord secureness.

A snap joint design approach under consideration, is also determined by which type of thermal plastic is selected. Major differences in material behavior exist between whether reinforced or non-reinforced thermal plastics are used. Thermal plastics are commonly reinforced by adding 10 to 40 percent glass fibers to the base resin. The addition of glass fibers can stiffen a base resin by 2 to 4 times but results in a significant loss of toughness. Because of this loss of toughness, snap fits utilizing reinforced plastics must be designed to operate below the yield strength to prevent snap fracture. In contrast, many non-reinforced plastics can be stressed much beyond the yield point and rebound or recover like rubber once the load is released. Therefore snap joints designed with non-reinforced plastics can be pushed to higher strain levels, which helps maximize the lateral stiffness of the joint. In abusive snap fit applications like prying, non-reinforced plastics also tend to be more robust because of the greater toughness.

Mechanics of a Cantilever Beam Snap Joint

The mechanics of a cantilever snap joint at the onset may seem quite simple but after close examination it is quite complex. Snap joint mechanics regarding snap installation or insertion is generally well understood and documented in many snap fit design guides. All snap joints typically have a lead-in ramp to provide some mechanical advantage to allow the snap beam to deflect easily until the snap catch has fully engaged with the mating surface. Analysis of the snap engagement phase has historically focused on calculating required insertion forces, lateral snap stiffness, and nominal bending stress levels at the root of the snap just before the snap catch is engaged. Rudimentary design equations have been developed using vector mechanics and beam bending formulas from basic strength of materials. Equally important and far more complex is the mechanics and analysis to predict the secureness or holding strength of a snap joint. In most cantilever snap joint designs, the snap catch is offset from the snap beam neutral axis of bending. As the snap catch is loaded in a pull mode, this offset distance between the point of contact under the snap catch and beam neutral axis, creates a bending moment at the end of the beam. This bending moment will cause the snap catch to rotate and start to cam-out. Once the snap catch surface has rotated to an angle greater than the critical friction angle, sliding and deflection of the snap catch surface progresses with the mating part until disengagement occurs. The maximum force required to cause the snap to cam-out is sometimes referred to as the snap pull strength or snap retention strength. Closed form analytical methods to predict the pull strength of a snap fit as influenced by snap catch rake angle, coefficient of friction between mating parts, snap beam lateral stiffness, snap support stiffness and snap catch length are very difficult to develop. Although, through the use of finite element programs like ANSYS with contact analysis and large deflection capabilities, these predictions of snap joint retention strength are now possible.

Development of Cantilever Snap Joint Finite Element Model

A generic two-dimensional finite element model of a tapered cantilever snap fit with mating snap surface was developed to investigate various factors influencing snap fit pull strength. The models were defined parametrically to allow for geometric parametric studies to be conducted easily by simply modifying parametric values. Provisions were made to adjust the snap catch rake angle, mating surface rake angle, size of snap beam support region and amount of beam taper or taper ratio. A separate contact region with the snap catch was also defined parametrically to adjust the contact rack angle. Since the deflection behavior of a snap beam is primarily two-dimensional, the cantilever snap and mating surfaces were modeled using plane42 elements with thickness input to define the snap width. This element type was also selected so that contact elements would not be associated with mid side nodes. Also, since non-linear contact analysis runs of this type can take several hundred iterations to converge, a two-dimensional model is more efficient than a three-dimensional model particularly when it is not required.

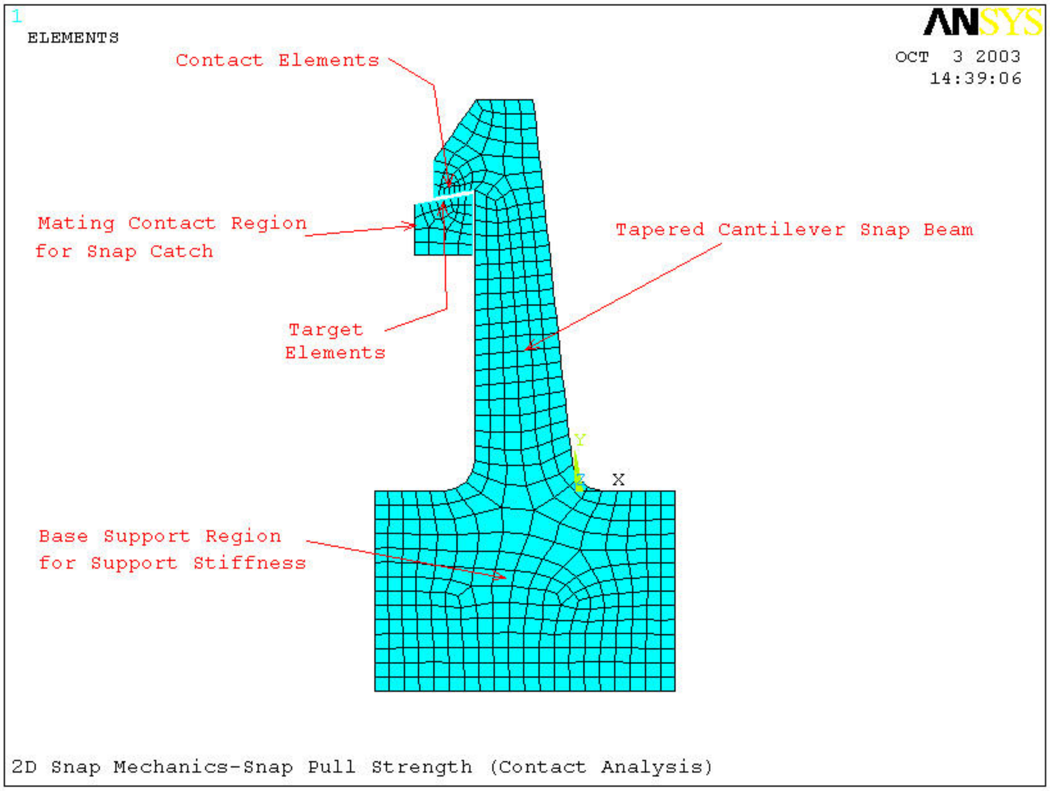

Figure 1. Finite Element Model of Tapered Cantilever Snap Joint

Contact behavior between the snap catch and mating surfaces were modeled by covering the mating peripheral surfaces with contact and target elements. The snap catch and mating surface regions were covered respectively with contact171 and target169 elements. Coefficient of friction between the two mating surfaces was also defined as a material constant for the contact elements. A support region around the base of the snap beam was also included in the model to capture the influence of support stiffness. Various size support regions were examined relative to the overall influence on the snap beam lateral stiffness. An appropriate support region size was selected, based on Saint Venants's principal that external boundary conditions if far enough away from the area of local interest, have little influence on the local solution. Nodes on the outer periphery of this support region were fixed in the ux and uy degrees of freedom directions. The solutions then progressed by incrementally moving the mating contact surface vertically in the y-direction until total cam-out of the snap beam catch surface occurred. Typical runs on a high end personal computer would required about 200-500 iterations and take about 2-10 minutes.

Modeling Considerations for Parametric Studies

A typical cantilever snap fit profile, molded in unfilled or non-reinforce thermal plastic, was selected for the parametric studies. Two models were developed to simulate maximum induced stress levels at the root of the snap beam during insertion and snap cam out behavior when a vertical pull load is applied. All variations snap beam geometries evaluated, were adjusted to have the same maximum bending stress at the root of the snap during insertion. This reduced any bias of snap design factors such as beam length, beam depth, and catch length from influencing other factors of interest. Snap catch length and plastic modulus of elasticity were also held constant for the parametric evaluations. Factors examined were, snap beam taper ratio, snap catch rake angle, snap beam width, and snap catch coefficient of friction regarding their influence on snap pull strength.

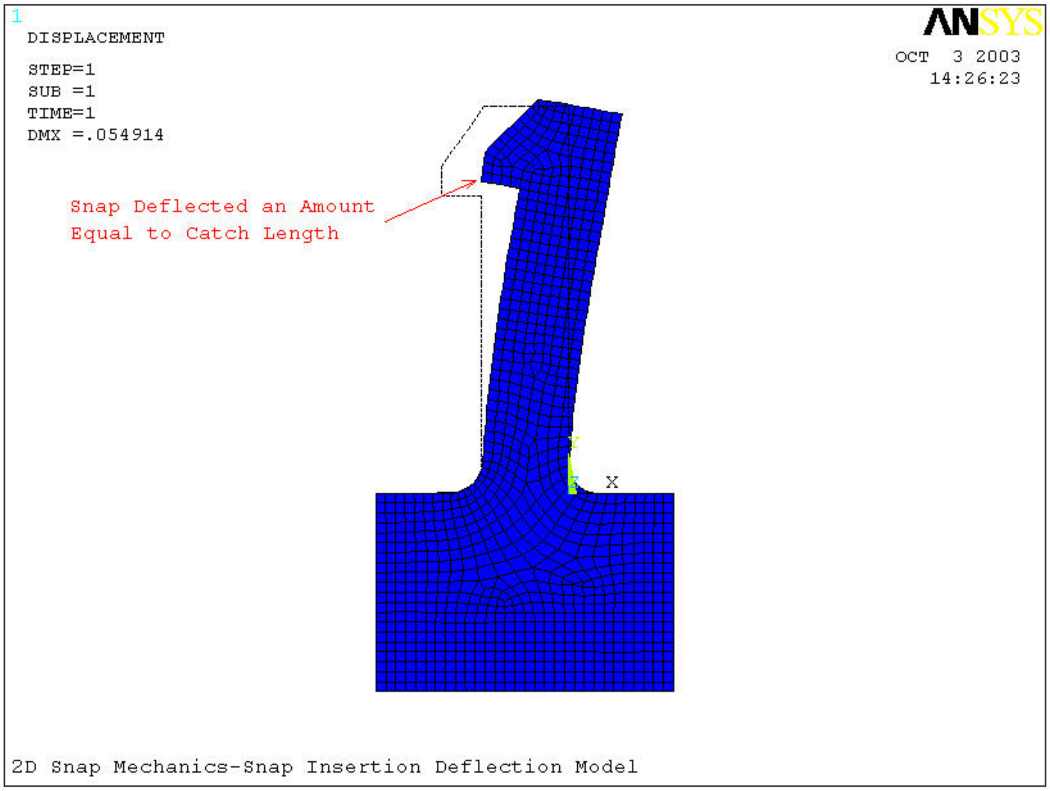

Figure 2. Snap Fit Insertion Deflection and Stress Model

Classical Analysis of Tapered Snap Cantilever Beam

To serve as a check and comparison with finite element analysis results, a classical model was developed for a generic tapered snap fit cantilever beam. Deflection formulas for constant cross section cantilever beams are readily available in any strength of materials text, but formulas for a generic tapered cantilever beam are hard to find. Therefore presented, is the development of deflection and stiffness equations for a generic tapered cantilever beam utilizing Castigliano's strain energy theorem, integrated using a five point Gauss-Legendre Quadrature method. The Gauss-Legendre Quadrature numerical solution to the strain energy integral was selected, because a closed form solution to this equation using classical calculus methods is difficult to obtain. A visual basic snap design program was then developed using the equations and methods presented in the following development. Shown in Figure 3 is a schematic diagram of the generic tapered cantilever snap beam examined with various beam parameters identified.

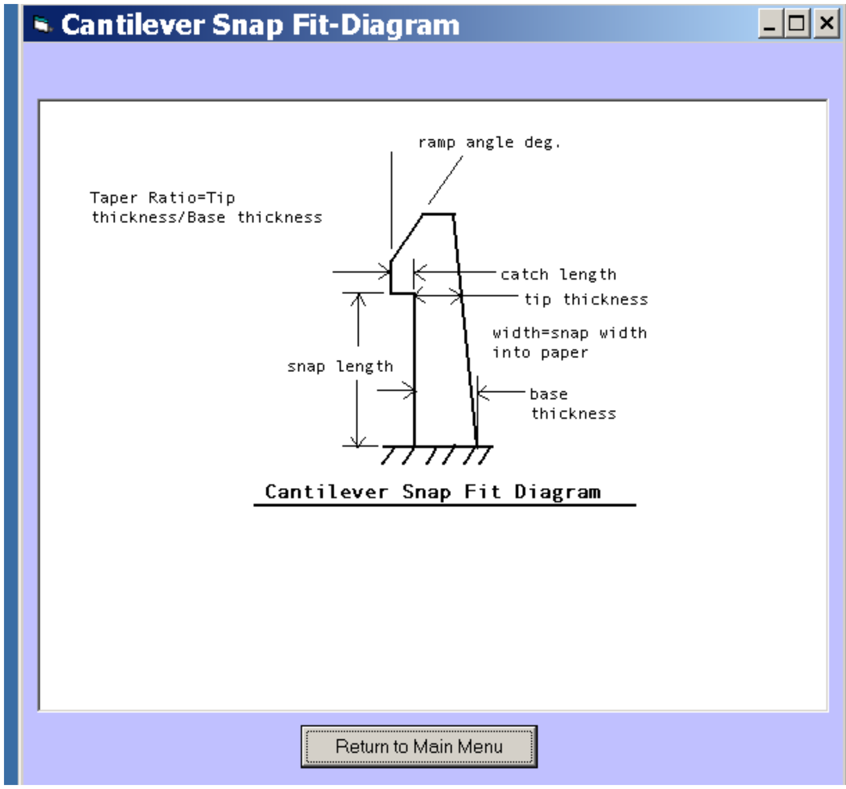

Figure 3. Diagram of Classical Analysis Tapered Snap Fit

Bending moment along the beam length as a function of x is equal to:

$$M(x)= P\,(L-x) \qquad (1)$$

Taking the partial derivative of bending moment M with respect to load P:

$$\partial M/\partial P= (L-x) \qquad (2)$$

This equation will be substituted into the Castigliano strain energy theorem.

For the tapered cantilever snap beam the section thickness as a function of x is equal to:

$$t\,(x)= ((t_t-t_b)/L)x + t_b \qquad (3)$$

With beam taper ratio R equal to:

$$R= t_t / t_b \qquad (4)$$

The beam section second moment of area as a function of x is equal to the following:

$$I\,(x) = 1/12\; W\, t^3\,(x) \qquad (5)$$

Castigliano's general strain energy theorem to evaluate beam deflection is equal to:

$$\delta= \int M / EI\;\; \partial M/\partial P\;\; dx \quad (6)$$

Substitution of (2) and (5) into the Castigliano equation and setting load P equal to 1 yields the following:

$$\delta= 1/E \int\; 12\,(L-x)^2/\,W\,t^3\,(x)\quad dx \;\text{ integrated from 0 to L} \qquad (7)$$

Snap Lateral stiffness K with a unit applied load P=1 is equal to the inverse of deflection δ:

$$K=1/\,\delta \qquad (8)$$

The integral in equation (6) is evaluated by using a 5 point Gauss-Legendre Quadrature and evaluated as follows:

$$\text{Integral} = L \sum f(\epsilon_i)\, H_i \qquad \text{summed from } i=1 \text{ to } 5 \qquad (9)$$

Where: ϵ_i = .5L, .2308L, .7692L, .04691L, and .9531L

H_i = .2844, .2393, .2393, .11845, and .11845

Once the snap fit beam lateral stiffness K has been determined then the lateral force P and maximum bending stress at the root of the beam can be determined from the following two equations:

$$P = K\,\delta \quad (10) \qquad \sigma = 6\,P\,L/\,W\,(t_b)^2 \quad (11)$$

A visual basic program was developed provide an easy user interface as well as perform the tapered snap fit beam calculations presented in the previous section.

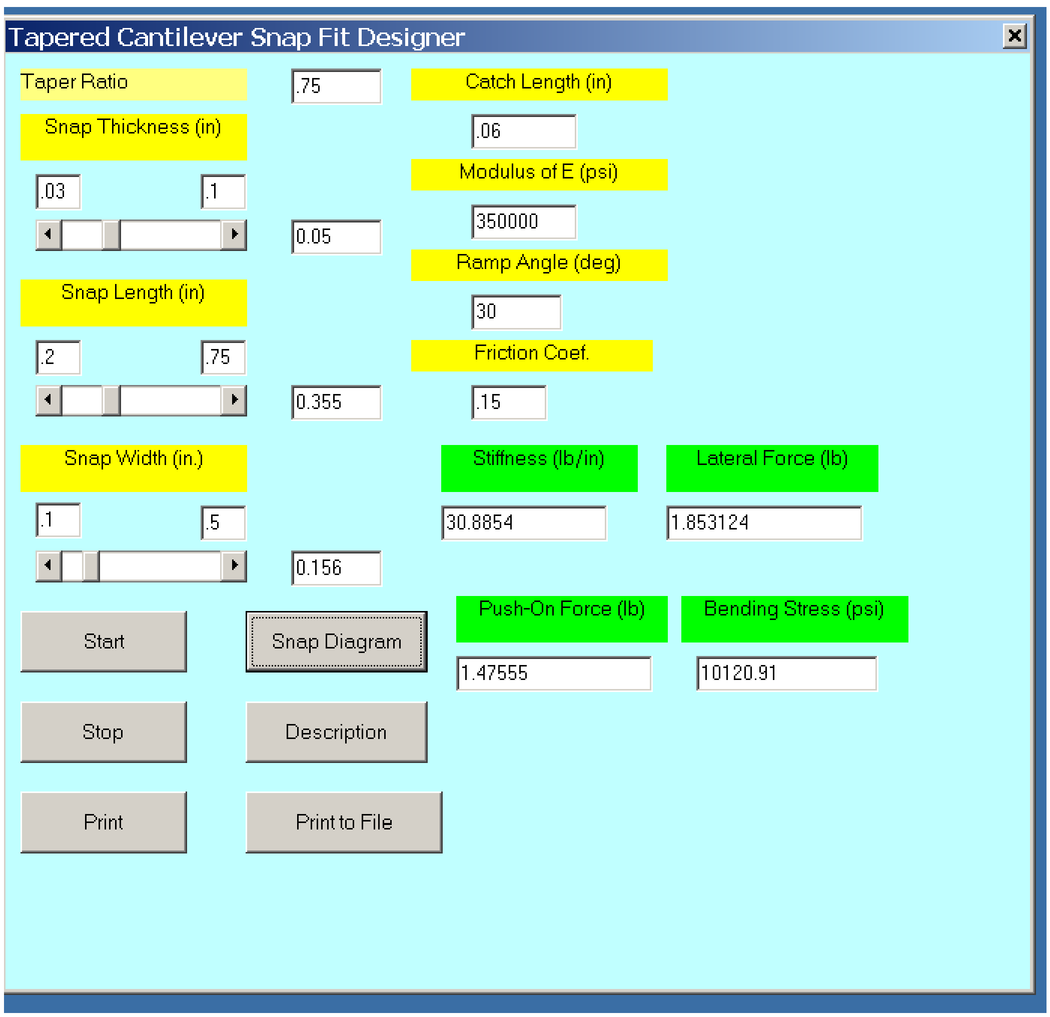

Figure 4. Tapered Beam Snap Fit Visual Basic Program

Analysis Results & Discussion

Non-linear contact analysis results were required to obtain an accurate prediction of snap fit pull strength as influenced by factors such as, support stiffness, rake angle, coefficient of friction, and snap lateral stiffness. Shown in Figure 5 is a sequence of four frames depicting the progression of snap cam out as the snap is loaded in a pull direction. From these pictures, it can be noted, that the snap catch initially rotates and then progressively slides off the engaged mating surface until total disengagement occurs. A typical plot of snap pull load versus vertical travel of the mating surface is shown in Figure 6. Initially the load rises linearly to a point and then flattens out horizontally until there is an abrupt drop off at the end where the snap has disengaged. The shape of a typical snap load versus deflection curve is similar to a stress-strain for a ductile material like low carbon annealed steel. The maximum load achieved in this load versus deflection plot is referred to as the snap pull strength.

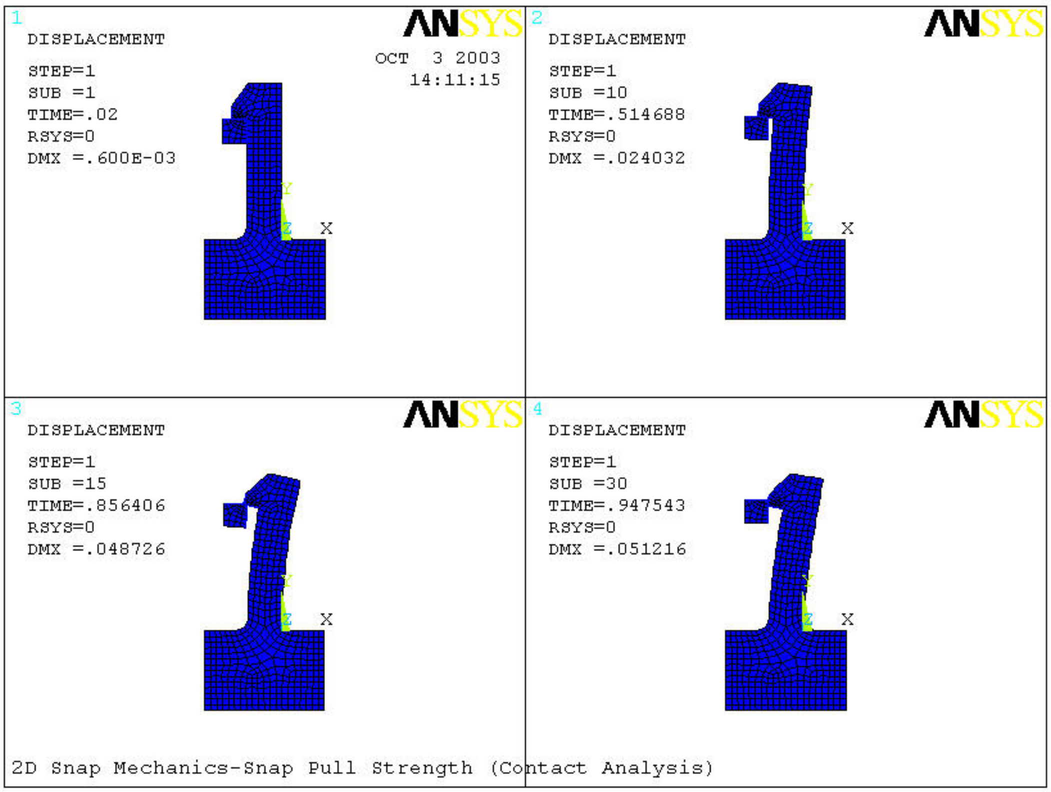

Figure 5. Deflection Sequence of Snap Cam Out Shown In Four Frames

Results for lateral stiffness obtained from the tapered snap beam classical analysis correlated very well with finite element results. This correlation required that the finite element model be supported rigidly at the snap base like a classical cantilever beam. Since the classical analysis approach doesn't consider any influence from the snap surrounding support material, a comparison of FEA to classical results is one method to assess the influence of support stiffness on the snap overall stiffness. Shown in Figure 6 is a plot of FEA and classical analysis results plotted as a ratio versus snap beam taper ratio. For the range of beam taper ratios from .5 to 1, the FEA to classical analysis ratio is almost constant at about .8. Therefore the finite element model predicted an influence of snap support stiffness of about 20 to 25 %. This indicates a deficiency in the classical analysis of predicting 20-25% higher lateral stiffness and stress levels on the snap beam.

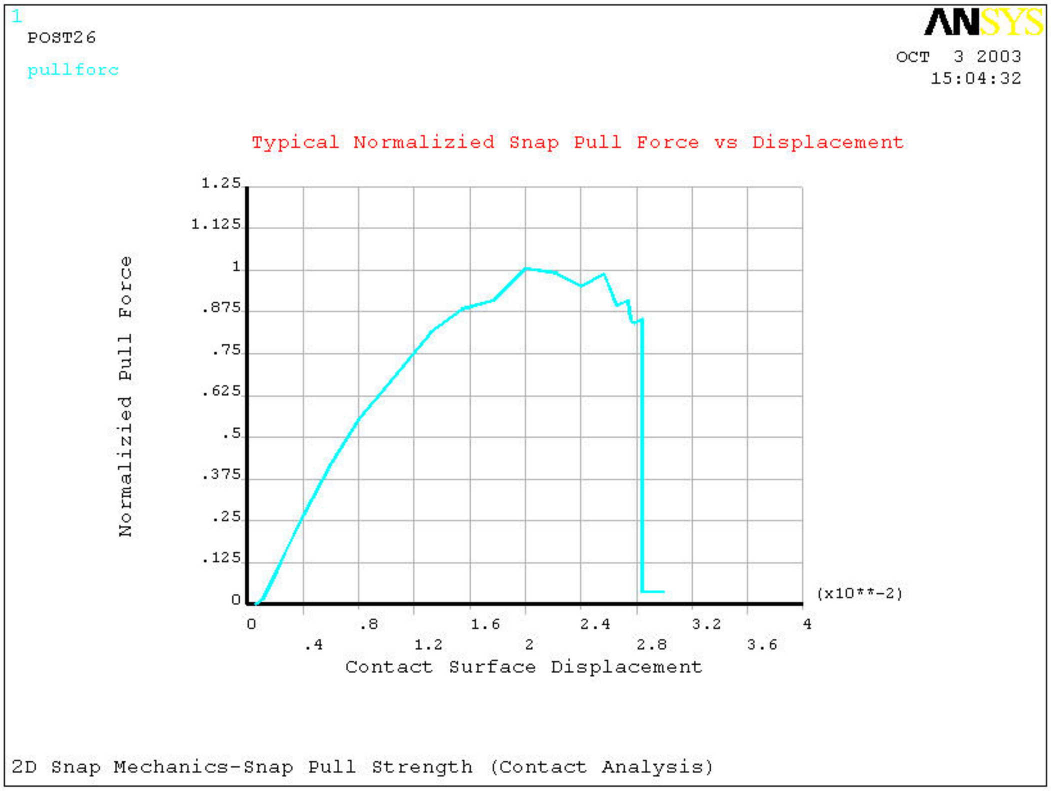

Figure 6. Typical Normalizied Snap Pull Force vs Deflection

Parametric studies were conducted to determine the influence of snap beam taper ratio, snap catch rake angle, snap beam width, and snap catch coefficient of friction on snap pull strength. Geometric parameters for all cases evaluated were adjusted based on snap insertion model results such that the same bending stress level at the root of the snap beam was achieved for all cases. By using this approach, the snap lateral stiffness could be maximized while still meeting the design constraint of all cases having the same stress level during snap insertion. Parameters held constant for all studies were material modulus of elasticity, beam length, snap catch length and size of the snap support region. A baseline model having a taper ratio of 1, rake angle of zero, width to thickness ratio of 3, and coefficient of friction equal to .25 was used as a frame of reference to normalize all parametric study results.

The three most significant factors influencing snap pull strength were found to be snap catch rake angle, snap beam width and coefficient of friction between mating surfaces. Normalized plots of these three major factors are shown respectively in Figures 8-10. Snap width is an obvious factor which influences snap pull strength based on basic beam theory. As snap width is increased, there is no influence on bending stress levels but lateral stiffness and snap pull strength increase linearly. One factor having little or no influence on snap pull strength was the beam taper ratio. This can be explained by the fact that as the beam becomes more tapered, the thickness of the snap beam near the catch region becomes thinner. With a thinner section, the catch as it is loaded will rotate and cam out more easily. Although coefficient of friction is a significant factor, in many cases this is a factor cannot easily be altered unless major changes in material selection are made.

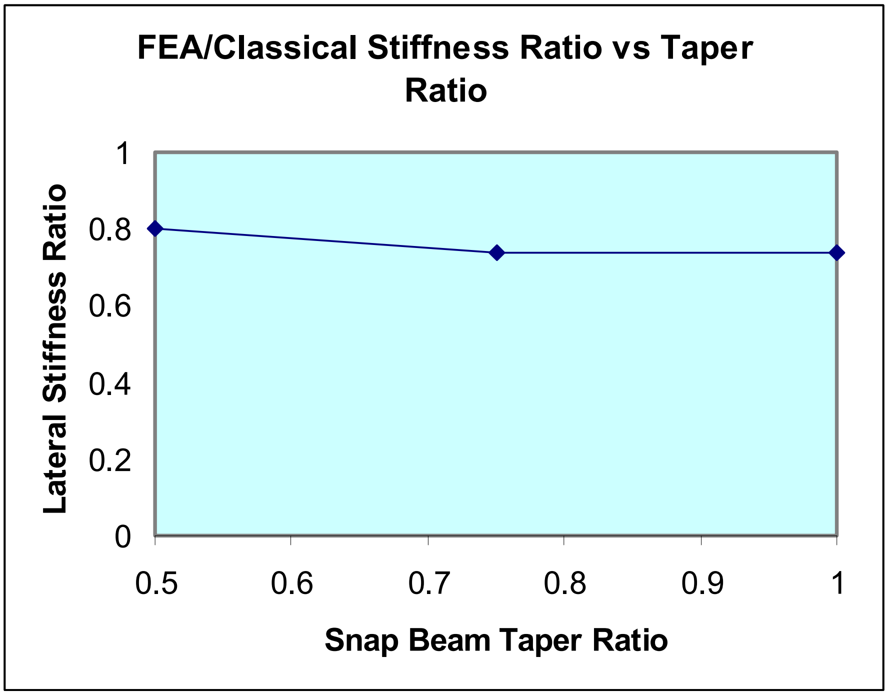

Figure 7. Influence of Support Stiffness on Lateral Stiffness

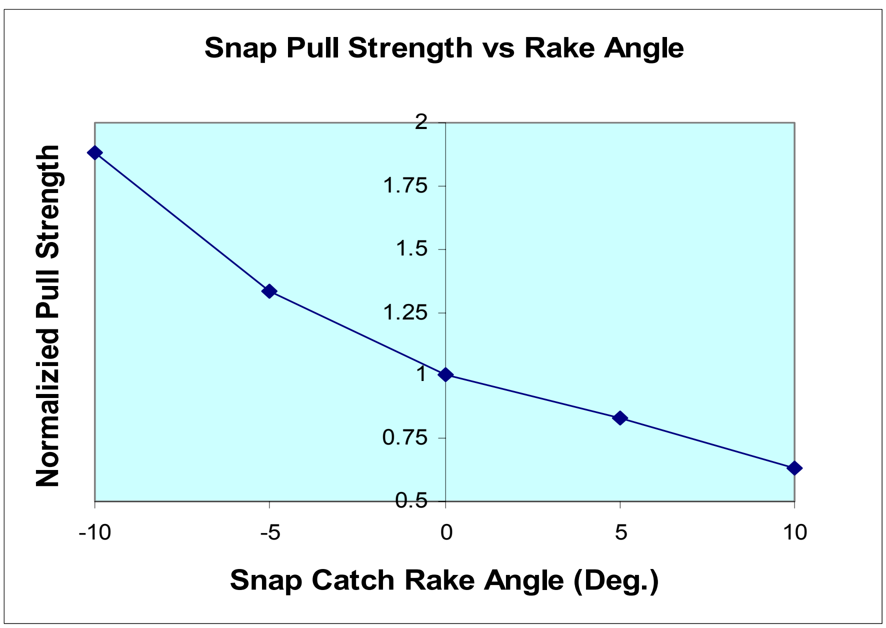

Figure 8. Snap Pull Strength vs Rake Angle

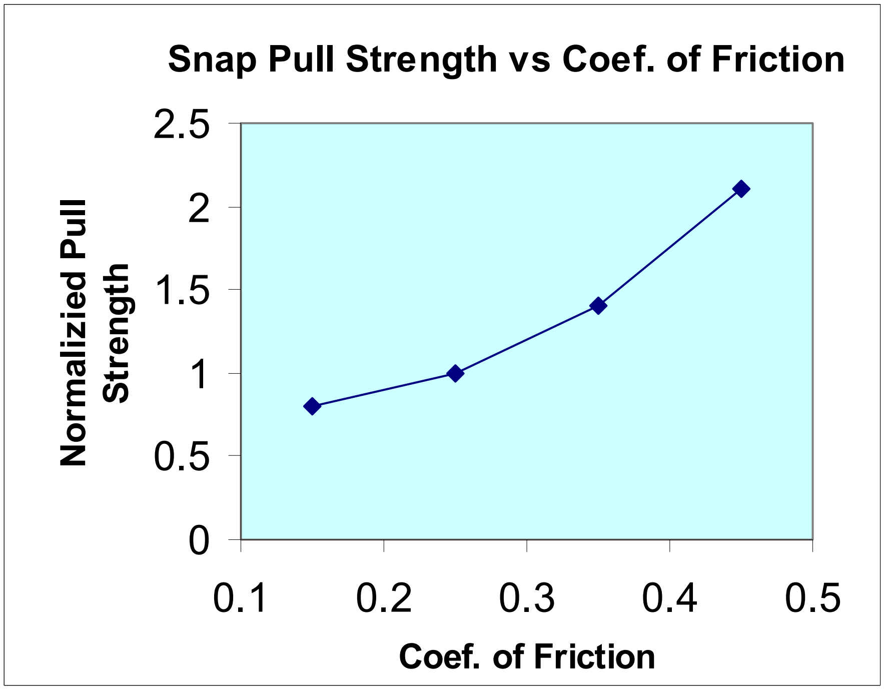

Figure 9. Snap Pull Strength vs Coef. of Friction

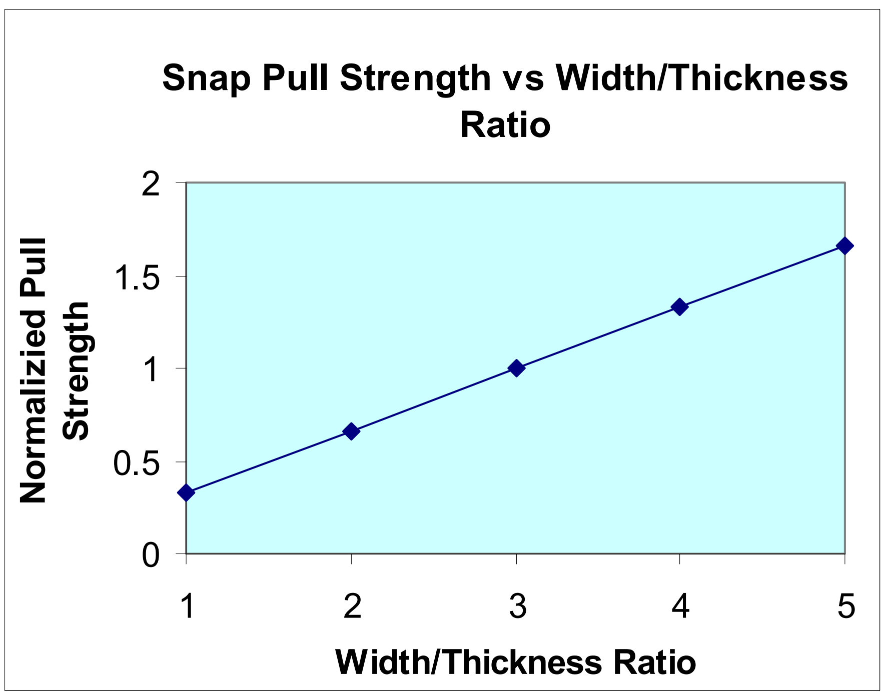

Figure 10. Snap Pull Strength vs Snap Width

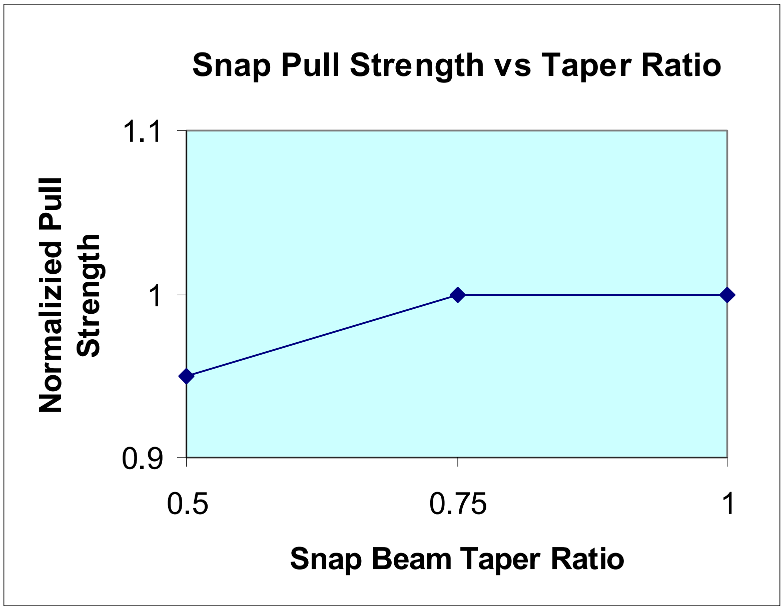

Figure 11. Snap Pull Strength vs Snap Beam Taper Ratio

Conclusion

Results and methods presented illustrate how non-linear contact analysis can be used to determine the pull strength of a simple cantilever snap joint. This approach can then be expanded to analyze more complex three dimensional snap fits found in products and assist with snap fit optimization prior to mold die fabrication. Results indicate that the most significant factors influencing the pull strength of a cantilever snap fit are snap beam width, catch rake angle and coefficient of friction between the snap catch mating surfaces. Technologies like ANSYS non-linear contact analysis and fast personal computers play a vital role in allowing engineers to optimize plastic molded components utilizing robust snap fits for their customers.

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