Structural optimization with manufacturing considerations

P. Fenyes
General Motors Research and Environmental Staff, 30500 Mound Road, Warren, MI 48090-9055, USA

Abstract Product design has traditionally been done in a sequential fashion. This often requires extensive iteration between product and manufacturing engineers to insure manufacturability long after the initial product design. Simultaneous engineering attempts to reduce design time by considering both the product and process from the earliest design stage. Toward this goal, we have extended a structural optimization program by incorporating manufacturability requirements for thin-wall beam type members formed by stamping. This was implemented using a new two-piece beam design element which accounts for thinning of the sidewalls during combined stretch and draw forming. Multiple material types and stamping processes are considered. Simple formulae for forming strain and elastic springback after stamping allow us to evaluate the formability of each beam member. The new capability was tested using both simple beam structures and a complete automotive frame structure. Minimum mass designs were then produced while considering both structural and formability requirements. In general, the mass of the optimal designs was near the mass of the same structures designed without manufacturing considerations. This was possible because of the additional design freedom offered by including the sidewall thinning effects.

1 Introduction

To remain competitive, new products must be brought to the marketplace quickly. Reducing the time required to design and tool a new product requires improvements in the basic design process. One of the identifiable bottlenecks in the current procedure is the transition from the product design phase to the process or manufacturing design phase. Often, long after the product has been designed, manufacturability issues are addressed for the first time. If manufacturing problems arise, considerable design changes may be required. Sometimes only a single part is affected, but often many of the mating parts will also require redesign. This is an extremely expensive and time-consuming process which may require several iterations between the product and process engineers to completely resolve. This is particularly true for stamped sheet metal parts which have many mating surfaces. To avoid this problem, it is necessary to simultaneously design for product and process. Although many computer tools exist for analysing product performance of manufacturing processes, they are generally incompatible and do not permit simultaneous analysis. For this reason we have added a simple forming analysis capability to our structural optimization program. Structural optimization is generally used in the early design phase and is ideally positioned in the design cycle to address the manufacturing issues up front, where they can have the greatest impact. Structural optimization has been used to design structures for minimum mass subject to various structural performance constraints such as stress, displacement, buckling, crashworthiness, and frequency of vibration. However, manufacturability analysis has not been considered for structures manufactured from sheet metal. The work of Ni et al. (1988) demonstrated simultaneous design of a single beam member with forming and structural constraints. This work extends their results to the design of complete structures with both standard structural requirements as well as manufacturing requirements.

To test the use of forming constraints with structural optimization it was necessary to create a new forming element with design variables related to the forming process as well as new constraints on the strain of forming and the elastic springback which occurs after forming. These will be described in the following sections.

2 A new design element for forming constraints

The new design element, a two piece closed channel section, is detailed in Fig. 1. The top of the section is a flat, unformed plate which is attached to the formed channel on the bottom. The closed channel section is described by seven independent design variables: the section widths \(w_1\) and \(w_2\), the section height \(h\), the thickness of the unformed top piece \(t_1\), the nominal thickness of the formed channel piece \(t_2\), the punch radius \(R\), and the sidewall thinning ratio which is defined as \(\tau = t_1/t_2\), where \(t_1\) is the final thickness of the sidewall after it stretches during forming. Accounting for the stretching yields a design element with three thicknesses, giving it additional design freedom when compared with the standard single thickness design element. By controlling the sidewall thinning parameter \(\tau\) it is possible to study different forming processes. For example, if we force \(\tau = 1.0\) the sidewalls maintain the nominal thickness, implying no stretching or thinning during forming. This type of behaviour would occur during a roll form or brake bending process (Datsko 1967), thus allowing us to analyse the feasibility of these processes and their impact on the structural mass.

The mass per unit length of the new design element is defined as the combined mass per unit length of the top and bottom pieces \(m = Ap\) where \(A\) is the cross-sectional area and \(p\) is the material density. The area is computed from the external dimensions, \(w_1\), \(w_2\), and \(h\) and the corresponding internal dimensions \(w_1t\), \(w_2t\), and \(ht\) as \(A = A_0 - A_i\) where \(A_0\) corresponds to the area of the outer trapezoid and \(A_i\) is the area of the inner trapezoid (Fig. 1). The width of the blank before forming is given by \(w_{\text{blank}} = A_2/l_2\), where \(A_2 = A - t_1w_1\) is the cross-sectional area of the bottom piece.
3 Simple forming constraints

The formability analysis evaluates two critical forming conditions: the material strain which occurs during stamping of the channel section and the elastic recovery or springback which occurs after stamping. Strain develops as the blank is bent and stretched by the punch and die. If the material is strained excessively, splitting occurs. The amount of strain which can be tolerated without failure is a material property. Springback, the elastic recovery which occurs after the channel is formed, causes the channel to widen slightly and diverge from the shape of the die (Fig. 2). The degree of springback which can be accepted depends on the dimensional accuracy required. Both strain and springback are complex functions of the forming conditions, punch and die geometry and lubrication, as well as the material properties and thickness of the blank. Accurate evaluation of forming strain and springback for general beam sections requires an iterative procedure to evaluate the stretching, bending and draw-in of the material. Detailed analysis of this type is available in several computer programs (Arlinghaus et al. 1985; Ni 1988; Frey and Wenner 1987), however, this is much too expensive to be used for all beam members of a structure since the forming constraints must be evaluated many times during each structural optimization iteration. For this reason, we have chosen the simple design element geometry shown in Fig. 1 whose forming properties can be approximated quite well using the explicit formulae of Ni et al. (1988)

\[ \epsilon_f = \epsilon_m + \epsilon_b, \quad \epsilon_m = \log(t_2/t_s), \quad \epsilon_b = \log(1 + \frac{t_2}{2R + t_s}). \]  

(1)

Here, \( \epsilon_f \) is the total strain of forming, \( \epsilon_m \) is the membrane or stretching strain, and \( \epsilon_b \) is the strain due to bending effects. The membrane strain is defined as the engineering strain (Crandall et al. 1978) and increases with greater thinning of the sidewalls. The bending strain occurs as the material wraps around the punch radius. It is inversely related to the punch radius and is influenced by the material thickness. The approximation (1) is based on a length-of-line analysis with bending effects at the punch radii and assumes the material in the bottom of the channel is locked by the punch during forming, causing all stretching to occur in the sidewalls. The detailed forming analysis given by Ni et al. (1988) has shown this to be a valid assumption.

Springback occurs after the forming process when the punch is removed from the die cavity and is the result of the elastic recovery of the sheet metal. It causes the channel opening to be slightly larger than the design width \( w_1 \). Springback is expressed as a change in the angle of the sidewalls and has been approximated by the following empirically derived formula (Ni et al. 1988)

\[ b\theta = \theta e^{\beta_1 \pi_1 + \beta_2 \pi_2 + \beta_3 \pi_3 + \beta_4 \pi_4 + \beta_5 \pi_5}, \]

where

\[ \theta = \text{(forming angle)}, \quad \pi_1 = R/t_s, \]
\[ \pi_2 = \mu \text{ (coefficient of friction)}, \]
\[ \pi_3 = 1 - \frac{\sigma}{\sigma_{\text{max}}}, \quad \pi_4 = \frac{c_1}{c_2}, \quad \pi_5 = c_3. \]

(2)

The parameters \( c_1, c_2, c_3 \) are material properties which govern the plane strain hardening law \( \epsilon = c_1 \sigma + c_2 \sigma_{\text{max}} \). The quantity \( \sigma \) is the stress due to forming and \( \sigma_{\text{max}} \) defines the ultimate stress of the material. These quantities can be computed from the forming strain and the ultimate strain, \( \epsilon_{\text{max}} \). The \( \pi \)'s were empirically determined and are given by Ni et al. (1988) as follows.

Preload case:

\[ \beta_0 = 0.461913, \quad \beta_1 = 0.6058, \quad \beta_2 = 0.0626, \]
\[ \beta_3 = 0.3495, \quad \beta_4 = 0.9852, \quad \beta_5 = 0.5611. \]

Postload case:

\[ \beta_0 = 0.230333, \quad \beta_1 = 0.4442, \quad \beta_2 = 0.09966, \]