THE PREDICTION OF DEFECTS OF A/C PRESSING

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Abstract

Flange bending is the frequent operation in A/C parts production - ribs, bulkheads, frames, stiffeners. The quality of products, pressings is dependant on their geometrical parameters and forming conditions. To avoid defects as f.e. cracs, warpings, uncomplete geometry, Forming Limit Diagrams (FLD) can be used, having border lines between good and not correct pressings.

The article brings the theoretical derivation of such limit lines, enabling to analyze quickly the influence of changed geometrical and forming conditions, minimizing thus the number of needed experiments. The described case reffers to convex flange bending by an elastic tool; loss of stability of the flange in elastic region propagates in plastic region by creation of permanent waves, wrinkles. Three border lines were theoretically derived, defining uncomplete geometry and wrinkling of pressings, respecting the hight of the flange (b), sheet thickness (t), radius of the convex flange (R) and tool pressure (p).

The secant and tangent modulae E_S, E_T and new definition of a material flow stress curve were used for transition from elastic to plastic state. The theory was successfully prooved by experiments.

Introduction to the problem

Pressing is supposed to be one of the leading technologies in the production of the airframe, the majority pieces of which are made of sheet metal, tubes and profiles. Ribs, webs, bulkheads, stiffeners, flat brackets, stiffened panels are typical parts of an airframe structure, the main feature of which are flanges, having straight, concave or convex contours. Flanges, as edge stiffeners, being simultaneously rigidity and joinging elements, can be unfortunately depreciated by some crack, warping and unfinished geometry. The generation of these defects can be in many cases predicted, prior to their appearance during the pressing process, using the analysis of technological formability of the problematic components.

Let's turn the attention to the convex flanges, which can suffer by permanent waves due to their unadequate geometrical parameters and technological unsufficiences.

It should be noted, that when the height and the shape of the wave are within the allowed limits it can be accepted as repairable, removable by some additional, very often manual operations.

A convex flange can be depreciated by plastic buckling due to the upsetting process of its lenght, when compressive stress originates the loss of stability. Realising, that this phenomenon obeys the same laws irrespective if it reffers to a convex flange plate or straight flat plate [(1)(3)], it is reasonable to make full use of the general equation of a critical stress, being valid in the elastic range [(1)(2)(5)]. It has the form

$$\sigma_{CR} = 0{,}9.K_T.E\left(\frac{t}{b}\right)^2, \qquad (1)$$

where generally $K_T = \frac{l.n^2}{b.m} + \frac{b.m}{l}$, m and n are numbers reflecting the number of sinusoidal half waves that buckle in the direction of l or b, when critical stress is reached and loss of stability starts. K_T is a coefficient, expressing not only the number of waves, but also influence of geometrical parameters, way of clamping of the elementary flange, incorporates the mode of outer loading, etc.

The state of stress of such a plate (flange) is slightly more complicated, while twist-bend loss of stability occurs influenced by St. Venant's stress including so called bending due to torque giving additional normal and shear stress.

The influence of non elastic range of strains is usually introduced in the eq (1) by the coefficient $\eta_e = E_e \cdot E^{-1}$, where E_e is the effective modulus, which is given, for the case of an rectangular element, by the traditional formula

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$$E_e = \frac{4.E\,E_T}{\left(\sqrt{E}+\sqrt{E_T}\right)^2}\ , \qquad (2)$$

where E_T represents a tangent module, $E_T = \frac{d\sigma}{d\varepsilon}$.

The definiton of E_T , regardeless to the knowledge of a material flow stress curve $\sigma = f(\varepsilon)$ acc. to [5] is not easy; that's why favoured are auxirially charts of relations between critical stress in non elastic range and value of stress in elastic range [5,8,9,10]. The recommended transcription reads

$$\sigma_{CRPl} = \eta_e \cdot \sigma_{CR}\ , \qquad (3)$$

The value of η_e has the interval $\eta_T = \frac{E_T}{E} \le \eta_e \le \eta_s = \frac{E_s}{E}$; $E_s = \frac{\sigma}{\varepsilon}$ is known as the secant modulus [11].

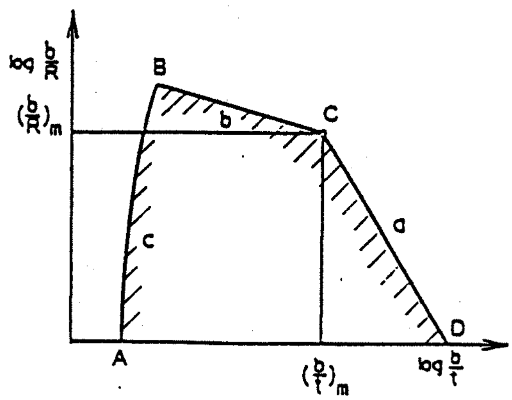

Fig. 1

The results of experiments [1,2] and theoretical solutions [3], relating to the operation of convex flange bending by an elastic tool, both enabled to plot a Forming Limit Diagram, see fig. 1, comprising the border lines, surrounding the area of good, acceptable processing. As a technological chart, its coordinate system is represented by geometrical parameters of components; here R denotes the outer radius of the developed, initial semiproduct; the border lines of the chart reflect the behaviour of the flange:

- a - elastic loss of stability
- b - plastic loss of stability
- c - uncomplete geometry of the bend.

<u>Definition of the border line "a"</u>

Bending of the flange having the width b is realized by elastic tool, exhibiting a uniformally disctributed pressure q_y. Considering the elastic compressibility of the tool, the pressure can be expressed by the equation

$$q_y = \frac{\Theta K b}{2}\left(1-\frac{b}{6R_o}\right)\ , \qquad (4)$$

and the corresponding moment with respect to flange medium line by

$$m_z = K\Theta\frac{b^2}{12}\left(1-\frac{3}{8}\frac{b}{R_o}\right)\ , \qquad (5)$$

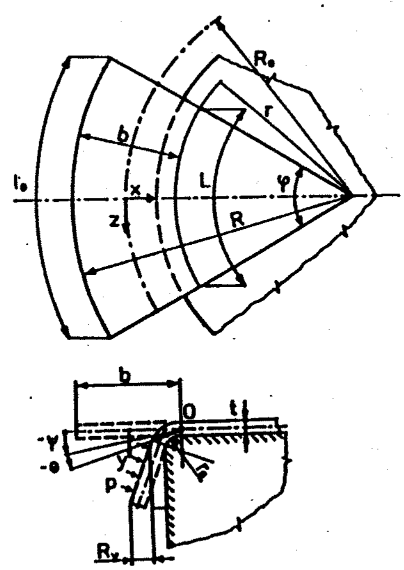

Fig. 2

where *K* [N/mm²] is an elasticity coefficient of the cushion tool; the geometry of the flange shows the fig. 2a. In the carried out theoretical calculations of the critical stress, when the loss of stability takes place, was the thickness of the flange substituted by the mean layer being gradually bent arround the point (0). Due to the upsetting process when R > r, (see fig. 2b) the bent flange section is simultaneously twisted by the angle ψ (fig. 2c). Here the reaction q_y and moment $c\Theta$ are acting as well, as the effect of the material continuity.

Conditions of equilibrium and relations between the twist angle Θ and displacement enable to express the equation, defining the obtained geometrical changes. The assumption, that the critical pressure force F_{CR} is acting at the distance $e = \frac{b}{6}$ from the axis of the loaded strip element was considered. The course of the twist angle $\Theta(s)$ is defined by differetial equation

$$\Theta^{IV} + 2a^2\Theta^{II} + a^4\Theta = 0\ , \qquad (6)$$

where

$$2a^2 = \frac{1}{EJ_e}\left(F_{CR}\left\{\left(\frac{b}{2}\right)^2 - r^2 + eb\right\} + \frac{EJ_x}{2R_o}b + GJ_k\left(\frac{b}{2R_o}-1\right)\right),$$

$$d^4 = \frac{1}{EJ_e}\frac{c}{3}\left(K_o + 3 - \frac{K_o}{16}\frac{b}{R_o}\right), \qquad K_o = \frac{Kb^2}{2c},$$

$$EJ_e = EJ_x\left(\frac{b}{2}\right)^2 + EJ_y\left(1 - \frac{b}{R_o}\right), \qquad r^2 = \frac{J_x + J_y}{A}.$$

The mentioned equations testify that the loss of stability was analyzed, considering not only bending of the crossection around the axis (x), but also its twisting; in the analysis the torsional rigidity was expressed by St. Venant's rigidity GJ_k and by the torsional - bending rigidity in the direction perpendicular to the medium line of the cross-section $EJ_y = E\frac{(bt)^3}{144}$; according to [5] $J_y = \Gamma_2$.

The equartion (6) enables to define the value of the critical stress having the well known form

$$\sigma_{CR} = K_T.E\left(\frac{t}{b}\right)^2. \qquad (7)$$

The eq. (7) is valid within the range of the Hook's law validity. Thus, the maximum value of this expression is reached at the point of the proportionality limit σ_{PR}, therefore

$$\sigma_{CR} = \sigma_{PR} = K_{Tm}.E\left(\frac{t}{b}\right)^2_m. \qquad (8)$$

Consequently it follows, that the border of the elastic wave propagation (see point C in the fig.1) is defined by the limit value of $\left(\frac{b}{t}\right)_m$ ratio as well.

$$\left(\frac{b}{t}\right)_m = \left(\frac{K_{Tm}.E}{\sigma_{PR}}\right)^{\frac{1}{2}}. \qquad (9)$$

The limit values of $\left(\frac{b}{t}\right)_m$ and $(K_T)_m$, obtained by "step by step" approximation of eq.(8) and (9), are needed for the definition of the point C coordinates.

For the next analysis there is necessary to calculate the number of the waves, having the shape of the lateral area of a cone (see fig.3). They have the maximum possible height, respecting the elastic tool behaviour and restriction of the flange size; their minimum number is

$$m_{min} = \frac{1}{\pi}\frac{R_0}{b}\varphi\left\{8\frac{b}{t}\frac{K_0\left(1 - \frac{1}{16}\frac{b}{R_0}\right) + 3}{\left(2\frac{r_0}{t} + 1\right)\left(4 - \frac{b}{2R_0}\right)}\right\}^{\frac{1}{4}}. \qquad (10)$$

There was prooved [14] that the number of the waves is not changed during the flanging process, but a half of them is loaded by compressive pressure, leading to the change of the radius R_p to R_r, as shown in fig. 3. The supposed normal stress in the wave is

$$\sigma = p\frac{R_v^2}{t}\frac{R_0 \pi m}{2bl_s}, \quad l_s = R_0\varphi . \qquad (11)$$

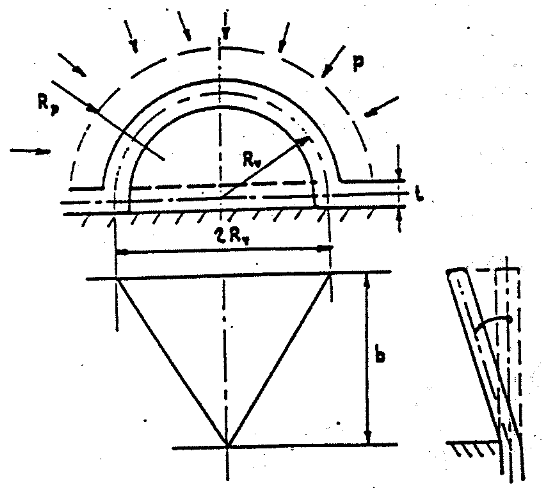

Fig. 3

Trying to defined another geometrical parameter of the flange, the relation between the relative elongation and the stress at the fringe of the flange seems to be usefull, thus

$$\frac{b}{R} = \frac{\sigma}{\sigma_K}\eta_K, \quad \sigma_K = R_{p0,2}, \qquad (12)$$

where limiting elastic stress, practically yield stress is defined as $\sigma_K = \varepsilon_K.E.\eta_K$.

Considering the above mentioned operations the eq. (12) has the form

$$\left(\frac{b}{R}\right) = \frac{p}{\sigma_K}\eta_K\frac{R_v^2}{tb}\frac{R_0}{b}\left\{\frac{b}{2t}\frac{K_0\left(1 - \frac{1}{16}\frac{b}{R_0}\right) + 3}{\left(2\overline{r_0} + 1\right)\left(4 - \frac{b}{2R_0}\right)}\right\}^{\frac{1}{4}}, \qquad (12)$$

where

$$\overline{r_0} = \frac{r_0}{t}, \qquad \frac{b}{2R_0} = \frac{1}{\frac{2R}{b} - 1}. \qquad (13)$$

The general dependance between the coordinates, defining the elastic region, considering the eq. (7) and (12), is

$$\frac{b}{R} = \frac{K_{Tm}.E}{\sigma_K}\eta_K\left(\frac{b}{t}\right)^{-2}. \qquad (14)$$

Using the point C, being defined by eq. (9) and (12) it is possible to plot in the graph fig (1) the elastic border limit as a line, having the slope (-2).

Definition of the border line "b"

The value of the critical stress in plastic region is defined by the equation

$$\sigma_{CR_{PL}} = \sigma_{CR_{EL}} \cdot \eta_e \quad . \qquad (15)$$

To express analyticaly the border line (b), see fig. 1, the transformation of the eq. (12) into the inelastic range was done, using the eq. (15). Considering the continuity of the searched function at the point C and accepting the eq. (12) and (15) is

$$\frac{b}{R} = \left(\frac{b}{R}\right)_m \left(\frac{b}{t}\right)_m^2 \left(\frac{t}{b}\right)^2 \eta_e \quad . \qquad (16)$$

Further step in calculation is possible, whem the value of the coefficient η_e is known. According to (12), if the results are to be on the safe side, the effective modulus can be substituted by the tangentional modulus, $\eta_e = \eta_T$. Consequently, to determine η_T a new flow stress function was proposed in (15) giving the advantage of simplier definition, thus

$$\sigma = \sigma_V^{\bar{m}} . \sigma_{EL}^{1-\bar{m}} \quad , \qquad (17)$$

$$\eta_T = \left(\frac{\sigma_{PR}}{\sigma_{CR}}\right)^n \quad , \qquad (18)$$

where σ_v is an arbitrary value of the flow stress in the proximity if the yield point; σ_{EL} that has hyperelastic behaviour, is $\sigma_{EL} = \varepsilon . E$. The exponent $\bar{m}$ is determined from the condition, that at a certain point of the flow stress curve, coincide the experimental and approximated value of the stress; very often is used $\sigma = \sigma_m = R_m$

$$\bar{m} = \left(\log\frac{\sigma_m}{\varepsilon E}\right)\left(\log\frac{\sigma_v}{\varepsilon_m E}\right)^{-1} , \qquad (19)$$

Using the previous equations for σ_{CR} and corrections for inelastic range (15) the resulting dependance between the geometrical parameters of the fange, when plastic wrinkling appears is

$$\left(\frac{b}{R}\right) = \left(\frac{b}{R}\right)_m \left(\frac{b}{t}\right)_m^{2(1-n)} \left(\frac{t}{b}\right)^{2(1-n)} . \qquad (20)$$

In the coordinates $\log b/R - \log b/t$ the equation (20) is represented by a straight line, having the slope -2(1-n) starting from the point C. It is clear, that when m = 1, then $\log b/R$ = konst.

Definition of the border line C

The field of "good" products in the forming limit chart is closed by a line C, see fig. 1. It represents the border, where the tool pressure is insufficient to finish a complete bent. Reasonably, this situation occurs when the width of the flange is narrow, there is no buckling or wrinkling. In the analysis a uniform distribution of the tool pressure p can be assumed whilevthe elasticity of the tool is depleted. The deviation from the nominal flange shape and uncomplete bent, measured at the fringe of the flange, is denoted by the symbol R_v, see fig. 2b.

The definition of the border line C is based on the solution of moments equilibrium. The general equation is

$$M_p + M_v + M_N = 0 \quad , \qquad (21)$$

where

$M_p = -\int_0^h p y\,dy$ bending moment of external pressure p

$M_v = 2\int_0^{t/2} \sigma y\,dy$ bending moment of internal forces

$M_N = \int_0^h p_N y\,dy$ bending moment of axial forces

The solution brought a slightly complicated resulting equation nevertheless plotting of the border line was possible.

In the solution, the suitability of the flow stress approximative function, eq. (17), was prooved.

Practical results

The proposed definition of the border lines was justiffied and prooved by solving a practical example, which was based on available experimental results presented by (14). Suitable material, duralumin, had following mechanical properties: σ_{PR} = 200 MPa, $R_{p0,2}$ = 280 MPa, R_m = 400 MPa, E = 7,06.10^4 MPa, ε_m = 0,14.

The results of calculations, being gathered bellow in some charts were compared with experimental values presented by (14); very good correlation was prooved.

The basic chart, fig. 4, shows the positive influence of the forming pressure p; its increase brings the enlargement of the field of correct pressings.

The influence of the tool elasticity is prooved by the chart in fig. 5. Lower elasticity causes the increase of the coefficient $K_C = \frac{K}{E}$, resulting in an enlargement of the good pressing field.

Comparatively important influence has the acceptable height of the wave which is characterized by R_v/t ratio, see fig. 6. As shown, the wave size could be managed also by the working pressure p.

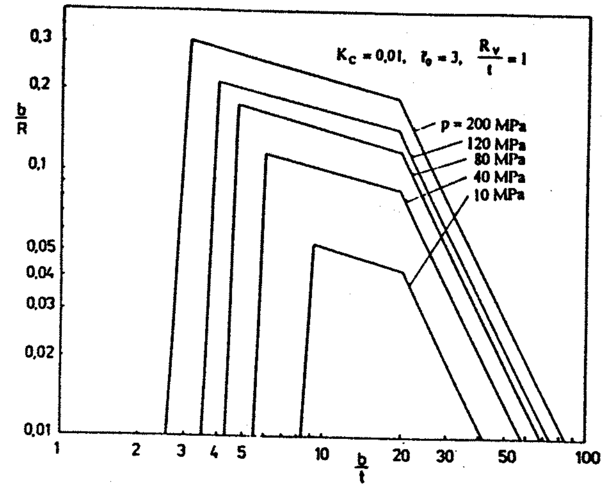

Fig. 4

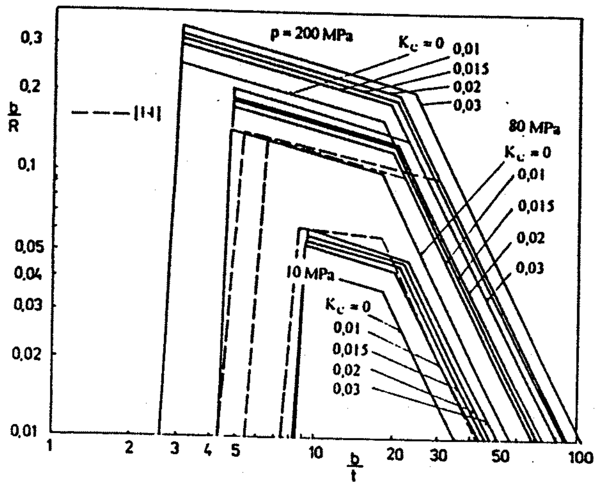

Fig. 5

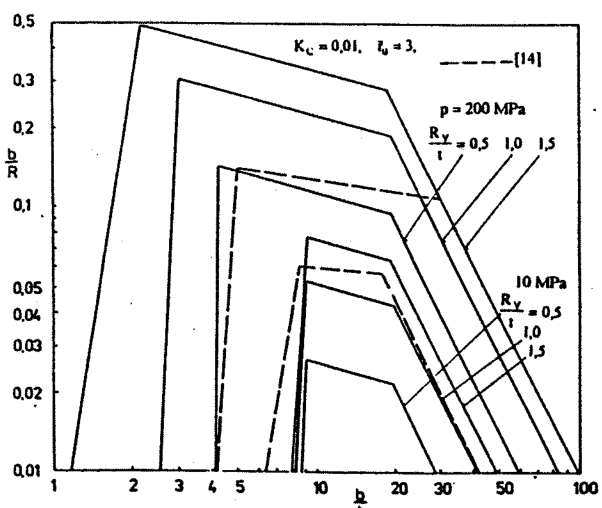

Fig. 6

The change of the radius r_0 has lesser influence, see chart in fig. 7. Moreover, the majority of components provided with flanges have nearly standardized values of r_0/t ratio, according to the component material.

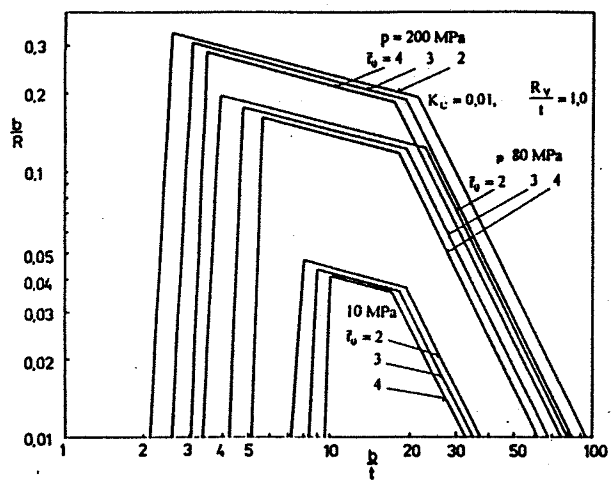

Fig. 7

Conclusion

Conterporary literature relating to the Forming Limit Charts of the discussed type brings a few informations about semiempirical derivation of the border lines. There exist some very simple, technological charts, having been plotted by means of experimental results. They usually comprise only one line and describe the influence of one geometrical parameter on the pressing quality. It is obvious, that the experiments were very much time and money consuming. The teoretical derivation of the border lines, the course of which could be veryffied only by some experiment, prooved to be very economic.

As shown in listed charts, the teoretical definition of the border lines enables to study very easy the influence of a change of the process parameters. The most decisive are the forming conditions, it means the working pressure p and the elasticity of the tool defined by the K_0 coefficient. The other parameters, r_0 and R_v, which influence on the pressing quality was also analysed, could be called as technological parameters. They are very often given, nearly standardized.

The another contribution of the teoretical work was a new definition of a material flow stress curve. The proposed approximation enables a very suitable and precisse definition of the secant and tangent modulae, which are frequently needed, when the loss of stability of thin wall structures is to be analysed.

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