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МАШИНОБУДУВАННЯ, АВТОМАТИЗАЦІЯ ВИРОБНИЦТВА ТА ПРОЦЕСИ МЕХАНІЧНОЇ ОБРОБКИ

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MATHEMATICAL MODEL OF EDGE CRACK DEVELOPMENT AT BENDING THIN-WALLED Z-SHAPED PROFILE

Taras Dovbush; Mukola Stashkiv; Nadiya Khomyk; Natalia Rubinets

Ternopil Ivan Puluj National Technical University, Ternopil, Ukraine

Summary. *We consider engineering methods for determining stress intensity factors for defective items open structure bending. Characteristic under development boundary cracks Z-shaped profile. The mathematical model and removed depending to calculate stress intensity factors for the two methods by nominal stress in the net section and by changing the axial cross-sectional moment of inertia Z-shaped profile. Investigated subcritical crack growth boundary, defined stress singularity in the vicinity of fatigue crack – stress intensity factors of the first kind, including models V.V. Panasyuk for pure tensile and bend. Analytical determined correction functions which account for changing the geometry of thin-walled structures with widespread fatigue crack on which the recorded intensity ratios for thin-walled profile elements who perceive tensile strain and pure bending. Graphs correction functions, having their approximation obtained generalized correction function Z-shaped profile 200x87x6 mm dimensions, which simplifies the calculation of residual life of structural elements of the system.*

Key words: *stress intensity factor, correction function, the length of the crack.*

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Problem setting. One of the most dangerous factors that lead to failures of hardware in agricultural production is the destruction of farm machinery basic load-bearing components during the operational processes due to loss of strength caused by formation and development of cracks under the complex influence of operational factors.

Increasing requirements for metal intensity and reliability of agricultural machinery structural systems are associated with providing strength and durability of their units and aggregates. The need for shortening the new technology design terms and the high cost of experimental research increase the value of experiment-calculated methods of structures durability assessment. Therefore, the development and justification of such methods is a complex task that requires in-depth analysis of calculation theory issues on strength of machinery load-bearing systems, as well as study and substantiation of new simulation models of crack development and load distribution in load-bearing systems, which altogether is an important scientific and technical task. Today the possibilities of agricultural machinery load-bearing components operating life assessment methods are not fully used. This work is aimed at the creation of a mathematical model of kinetics of edge cracks in thin structural elements of machinery under cyclic loading.

Corresponding author: Natalia Rubinets; e-mail: natalyarubinets@gmail.com

Analysis of recent research and publications. Development of analytical dependence for determining the operational life of load-bearing units of agricultural machines at dynamic loading of thin-walled elements with cracks and actual performance impacts are shown in [1, 2]. The work [3] shows analytical study to determine the stress intensity factor of some open and closed thin sections which are used to determine the remaining operational life of the system structural elements.

Research objectives are to:

- create a mathematical model of subcritical growth of boundary crack in thin-walled cold-formed profiles of elements of Z-shaped cross sections of load-bearing metal machinery structures;
- analytically determine the correction functions which take into account changing of thin-walled structures geometry caused by the expansion of fatigue crack, and on this base find the intensity factor for Z-shaped cross sections that receive tensile strain and pure bending strain;
- build correction function graphs which take into account changing of thin Z-shaped profiles geometry caused by fatigue crack expansion to flange and wall, do their approximation and obtain the generalized correction function of 200x87x6 mm Z-shaped profile.

Task setting. Analytically determine the correction functions which take into account changing of the geometry of Z-shaped cross-section in crack development process, namely for flanges and walls. Build graphs of correction functions, approximate them and get generalized correction function for 200x87x6 mm Z-shaped profile.

Research results. Upon building computer simulation models of stress-strain state of load-bearing structural systems taking into account actual loading and using a modified method of minimum potential energy deformation [4, 5], we identified dangerous intersections of likely origin of cracks.

In open cross sections the area of probable beginning of the crack is the edge of the intersection, where the stress concentrators caused by welded seams are located.

For a simulation model to determine the stress intensity factor K_I let us select an edge fatigue crack that develops in a thin-walled Z-shaped intersection of spreader spar frame.

*T*o describe the growth of an edge crack consider a thin-walled Z-shaped profile (Fig. 1) loaded with bending moment M as to the axis Y.

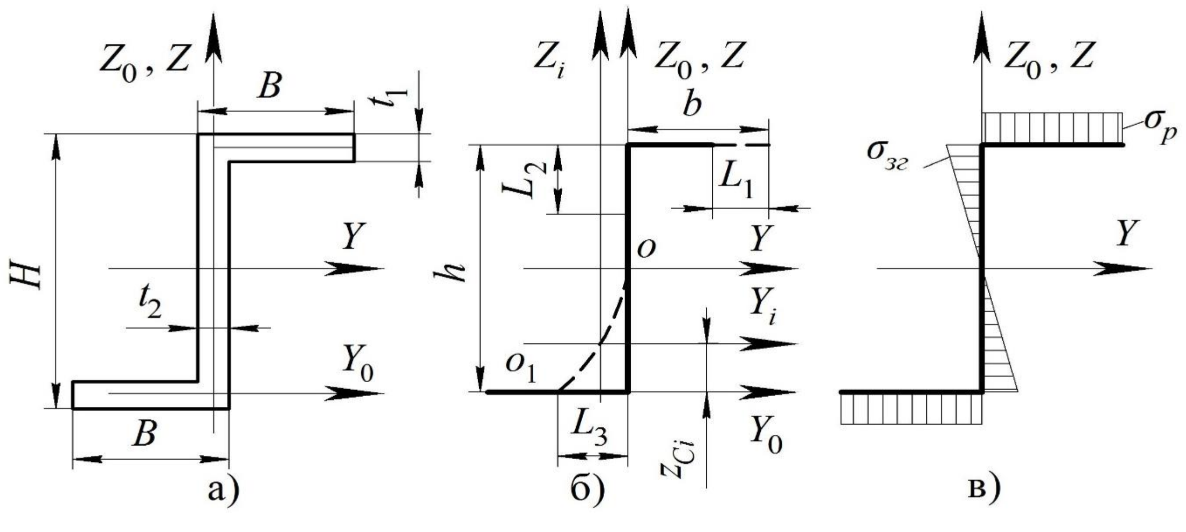

Figure 1. Diagram to determine the geometrical characteristics of thin-walled profile with an edge crack: а) schematization Z-shaped cross-section; б) schematization Z-shaped cross section with an edge crack, O-O_1 – trajectory shift the center of gravity in the development of cracks; в) distribution of stresses in the defect-free cross-section

The influence of bending moment on the thin-walled profile will cause its horizontal flanges to stretch and the vertical ones to bend. We can simulate with certain approximation stressed state that occurs in the walls of a rectangular profile with a crack if we consider each wall as a separate plate of the same thickness and width with a side crack at similar power load.

Solutions to problems of determining the stress intensity factor at the top of opening mode fatigue crack can be similar to the dependences obtained in [6]:

- stretching

$$K_I^{(t)} = \sigma_{nom}^{(t)} \cdot (1-\varepsilon)\sqrt{L\cdot\pi} \times \left[1 + 0{,}128\varepsilon - 0{,}288\varepsilon^2 + 1{,}525\varepsilon^3\right]; \tag{1}$$

- bend

$$K_I^{(b)} = \sigma_{nom}^{(b)} \cdot (1-\varepsilon)^2\sqrt{L\cdot\pi} \times \left[1{,}122 - 1{,}4\varepsilon + 7{,}33\varepsilon^2 - 13{,}08\varepsilon^3 + 14\varepsilon^4\right], \tag{2}$$

where ε – crack length / flange width ratio, $\varepsilon = \frac{L}{b}$;

$\sigma_{nom}^{(t)}$ and $\sigma_{nom}^{(b)}$ – nominal stretching and bending strains respectively, MPa.

Tension $\sigma_{nom}^{(t)}$ and $\sigma_{nom}^{(b)}$ must be selected so that they fully meet the real picture of the distribution of stresses in a section of flanges with crack. This task is to determine the stress-strain state in cross section with a crack under the influence of bending moment *M*.

Theoretically, thin-walled profile of Z-shaped cross-section collapses when the total length of the crack reaches the size (see. Fig. 1)

$$L = L_1 + L_2 + L_3, \tag{3}$$

where L_1 – the length of the edge crack at the first stage of its development ($0 \le L_1 \le b$; $L_2 = L_3 = 0$); L_2 – length of edge crack at the second stage of its development ($0 \le L_2 \le h$; $L_1 = b$; $L_3 = 0$); L_3 – length of edge crack at the third stage of its development ($0 \le L_3 \le b$; $L_1 = b$; $L_2 = h$).

Common expressions that describe the change of coordinates of the center of mass z_{Ci} and axial cross-sectional moment of inertia I_{Yi} at the crack spreading are determined by the formula [3] (see. Fig. 1):

$$z_{Ci} = \frac{\sum_{i=1}^{n} F_i \cdot z_i}{\sum_{i=1}^{n} F_i} = \frac{(b-L_1)\cdot t_1 \cdot h + (h-L_2)\cdot t_2 \cdot \frac{h-L_2}{2}}{(b-L_1)\cdot t_1 + (h-L_2)\cdot t_2 + (b-L_3)\cdot t_1}; \tag{4}$$

$$I_{Yi} = \frac{(b-L_1)\cdot t_1^3}{12} + (b-L_1)\cdot t_1 \cdot (h-z_c)^2 + \frac{(h-L_2)^3\cdot t_2}{12} + \\ + (h-L_2)\cdot t_2 \cdot \left(\frac{h-L_2}{2} - z_c\right)^2 + \frac{(b-L_3)\cdot t_1^3}{12} + (b-L_3)\cdot t_1 \cdot (z_c)^2. \tag{5}$$

Axial moment of inertia of a zero-defect Z-shaped cross-section

$$I_Y = \frac{b \cdot t_1^3}{12} + b \cdot t_1 \cdot \left(\frac{h}{2}\right)^2 + \frac{h^3 \cdot t_2}{12} + \frac{b \cdot t_1^3}{12} + b \cdot t_1 \cdot \left(\frac{h}{2}\right)^2. \tag{6}$$

Determine the stress-strain state of intersection at each stage of crack development considering that a thin-walled rod (Fig. 1a) accepts pure bending (rotation of axes does not occur).

The first stage of the crack. Geometric characteristics of cross-section at $L = L_1$, $L_2 = L_3 = 0$:

$$z_{Ci} = \frac{h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t_2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2}; \tag{7}$$

$$\begin{aligned} I_{Yi} = {} & \frac{b \cdot t_1^3}{12} + \frac{1}{12}(b - L) \cdot t_1^3 + \frac{h^3 \cdot t_2}{12} + \\ & + \frac{b \cdot t_1 \cdot \left[h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2}\right]^2}{\left[b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2\right]^2} + h \cdot t_2 \cdot \left[\frac{h}{2} - \frac{h(b - L) \cdot t_1 + \frac{h^2 t_2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2}\right]^2 + \\ & + (b - L) \cdot t_1 \cdot \left[h - \frac{h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2}\right]^2. \end{aligned} \tag{8}$$

Nominal strains in a profile flange are determined from the equation [3]

$$\sigma_{nom}^{(t)} = \frac{M\left(h - z_{c_{1i}}\right)}{I_{Y_{1i}}}. \tag{9}$$

Substituting (7) and (8) to (9) we obtain

$$\sigma_{nom}^{(t)} = \frac{M\left(h - \frac{h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t_2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2}\right)}{\left\{\begin{aligned} & \frac{b \cdot t_1^3}{12} + \frac{1}{12}(b - L) \cdot t_1^3 + \frac{h^3 \cdot t_2}{12} + \frac{b \cdot t_1 \cdot \left[h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2}\right]^2}{\left(b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2\right)^2} + \\ & + h \cdot t_2 \cdot \left[\frac{h}{2} - \frac{h(b - L) \cdot t_1 + \frac{h^2 t_2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2}\right]^2 + \\ & + (b - L) \cdot t_1 \cdot \left[h - \frac{h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2}\right]^2 \end{aligned}\right\}}. \tag{10}$$

For a defect-free profile maximum coordinates of the center of mass $z_C = h/2$, then $\sigma = \frac{M}{I_Y} \cdot \frac{h}{2}$. If $\varepsilon = \frac{L}{2b+h}$, then $L = \varepsilon(2b+h)$. Substituting obtained dependences and expression (10) in the stress intensity factor equation (1) we obtain the stress intensity factor expression in the case of a crack development in a Z-shaped thin-walled profile flange.

$$K_I^{(t)} = \frac{M}{I_Y} \cdot \frac{h}{2} \sqrt{\pi \cdot L_1} \cdot F_1(\varepsilon), \qquad (11)$$

where $F_1(\varepsilon)$ – dimensionless correction factor for the change in the geometry of the thin-walled profile flange at the propagation of a fatigue crack in it.

$$\begin{aligned} F_1(\varepsilon) = \{ & h \cdot (12{,}2 \cdot b^3 + 18{,}3 \cdot b^2 \cdot h + 9{,}15 \cdot b \cdot h^2 + 1{,}525 \cdot h^3) \times \\ & \times (2 \cdot b \cdot t_1 + h \cdot t_2) \cdot (6 \cdot b \cdot h^2 \cdot t_1 + 2 \cdot b \cdot t_1^3 + h^3 \cdot t^2) \cdot (0{,}78 + \varepsilon) \times \\ & \times [h + b \cdot (2 - 2 \cdot \varepsilon) - 1 \cdot h \cdot \varepsilon] \cdot (0{,}84 - 0{,}97 \cdot \varepsilon + \varepsilon^2) \} \div \\ \div \Bigg\{ & (2 \cdot b + h)^4 \cdot (h + t_1) \cdot \Bigg[b^2 \cdot t_1^2 \cdot \Bigg[h^2 \cdot \Big(12 - 24 \cdot \varepsilon \Big) + 4 \cdot t_1^2 \cdot (-1 + \varepsilon)^2 \Bigg] + \\ & + h^2 \cdot \Bigg[h^2 \cdot t_2 \cdot (t_2 - 4 \cdot t_1 \cdot \varepsilon) + t_1^3 \cdot \varepsilon \cdot \Big(-1 \cdot t_2 + t_1 \cdot \varepsilon \Big) \Bigg] + \\ & + b \cdot h \cdot t_1 \cdot \Bigg\{ h^2 \cdot \Bigg[t_2 \cdot (8 - 8 \cdot \varepsilon) - 12 \cdot t_1 \cdot \varepsilon \Bigg] + \\ & + t_1^2 \cdot \Bigg[t_2 \cdot (2 - 2 \cdot \varepsilon) + t_1 \cdot \varepsilon \cdot \Big(-4 + 4 \cdot \varepsilon \Big) \Bigg] \Bigg\} \Bigg] \Bigg\}. \end{aligned} \qquad (12)$$

The second stage of the crack. Geometric characteristics of Z-shaped cross section at $L = b + L_2,\ L_3 = 0$:

$$z_{C_2} = \frac{(b + h - L)^2 \cdot t_2}{2 \cdot [b \cdot t_1 + (b + h - L) \cdot t_2]}; \qquad (13)$$

$$\begin{aligned} I_{Y_2} = & \frac{b \cdot t_1^3}{12} + \frac{1}{12}(b - L) \cdot t_1^3 + \frac{h^3 \cdot t_2}{12} + \frac{b \cdot t_1 \cdot \left(h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2} \right)^2}{(b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2)^2} + \\ & + h \cdot t_2 \cdot \left(\frac{h}{2} - \frac{h(b - L) \cdot t_1 + \frac{h^2 t_2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2} \right)^2 + \\ & + (b - L) \cdot t_1 \cdot \left(h - \frac{h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2} \right)^2. \end{aligned} \qquad (14)$$

Nominal stresses in the wall of a thin-walled Z-shaped profile are determined from the equation [3]

$$\sigma_{nom}^{(b)} = \frac{M \cdot \left(h - L_2 - z_{C_2}\right)}{I_{Y_{2i}}}. \tag{15}$$

Substituting (13) and (14) to (15) we obtain

$$\sigma_{nom}^{(b)} = M \cdot \left(h - L_2 - \frac{(b + h - L)^2 \cdot t_2}{2 \cdot \left(b \cdot t_1 + (b + h - L) \cdot t_2\right)} \right) \div$$
$$\div \left(\frac{b \cdot t_1^3}{12} + \frac{1}{12}(b - L) \cdot t_1^3 + \frac{h^3 \cdot t_2}{12} + \frac{b \cdot t_1 \cdot \left(h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2} \right)^2}{\left(b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2\right)^2} + \right.$$
$$+ h \cdot t_2 \cdot \left(\frac{h}{2} - \frac{h(b - L) \cdot t_1 + \frac{h^2 t_2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2} \right)^2 + \tag{16}$$
$$\left. + (b - L) \cdot t_1 \cdot \left(h - \frac{h \cdot (b - L) \cdot t_1 + \frac{h^2 \cdot t^2}{2}}{b \cdot t_1 + (b - L) \cdot t_1 + h \cdot t_2} \right)^2 \right).$$

For a defect-free Z-shaped profile maximum coordinate is $z_C = h/2$, strain $\sigma = \frac{M}{I_Y} \cdot \frac{h}{2}$ and if $\varepsilon = \frac{L}{2b + h}$ then $L = \varepsilon(2b + h)$. Substituting obtained dependences and expression (16) in equation (2) we obtain an expression of stress intensity factor for the case of a crack in the wall of a thin-walled Z-shaped profile

$$K_I^{(b)} = \frac{M}{I_Y} \cdot \frac{h}{2} \sqrt{\pi \cdot L_2} \cdot F_2(\varepsilon), \tag{17}$$

where $F_2(\varepsilon)$ – dimensionless correction factor for the change in the geometry of thin-walled wall profile at the propagation of fatigue crack in it.

$$F_2(\varepsilon) = \left\langle 28 \cdot \left[2 \cdot b \cdot \left(3 \cdot h^2 \cdot t_1 + t_1^3\right) + h^3 \cdot t_2\right] \cdot \left(-1 + \varepsilon \right)^2 \times \right.$$
$$\times \left(0{,}50 - 1{,}069 \cdot \varepsilon + \varepsilon^2\right) \cdot \left(0{,}157 + 0{,}134 \cdot \varepsilon + \varepsilon^2\right) \times$$
$$\times \left(b + h - (2 \cdot b + h) \cdot \varepsilon - \left\{ t_2 \cdot \left[b + h - (2b + h) \cdot \varepsilon \right]^2 \right\} \div \right.$$

$$\div \left[2\cdot\left\{ b\cdot t_1 + t_2\cdot\left[b+h-(2\cdot b+h)\cdot\varepsilon \right]\right\}\right]\Big)\Big\rangle \div \;\div (h+t_1)\cdot\left\{ b\cdot t_1^3 + t_2\cdot\left[b+h-(2\cdot b+h)\cdot\varepsilon \right]^3\right\}+$$
$$+3\cdot b^2\cdot t_1^2\cdot t_2\cdot\left[b+h-(2\cdot b+h)\cdot\varepsilon \right]^3 \div \;\div\left\{ b\cdot(t_1+t_2)+t_2\cdot\left[h-(2\cdot b+h)\cdot\varepsilon \right]^2\right\}+ \quad (18)$$
$$+3\cdot b^2\cdot t_1^2\cdot t_2\cdot\left[b+h-(2\cdot b+h)\cdot\varepsilon \right]^4 \div \;+\left\{ b\cdot t_1+t_2\cdot\left[b+h-(2\cdot b+h)\cdot\varepsilon \right]^2\right\}.$$

For thin-walled Z-shaped profile with dimensions of 200×87×6 mm correction functions in graphical form are shown in Fig. 2.

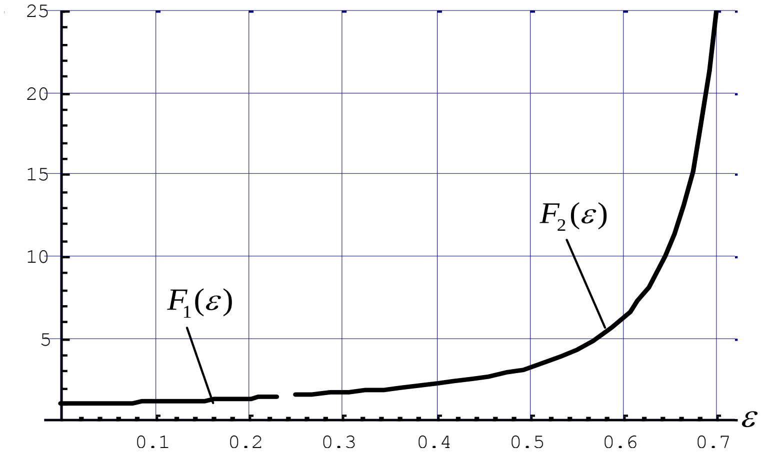

Figure 2. Dependence functions *F* for defects *ε*
Z-shaped thin-walled profile with dimensions 200×87×6 mm

We approximate functions $F_1(\varepsilon)$ and $F_2(\varepsilon)$ (see. Fig. 2) and obtain a generalized correction function for a 200×87×6 mm Z-shaped cross-section

$$F(\varepsilon)=1-2{,}586\cdot\varepsilon+132{,}249\cdot\varepsilon^2-1628{,}850\cdot\varepsilon^3+5035{,}670\cdot\varepsilon^4+$$
$$+54598{,}249\cdot\varepsilon^5-579311{,}0\cdot\varepsilon^6+2{,}457\cdot10^6\cdot\varepsilon^7-5{,}753\cdot10^6\cdot\varepsilon^8+ \quad (19)$$
$$+7{,}786\cdot10^6\cdot\varepsilon^9-5{,}724\cdot10^6\cdot\varepsilon^{10}+1{,}775\cdot10^6\cdot\varepsilon^{11}.$$

Conclusions. The mathematical models of edge crack development at bending of a thin-walled Z-shaped profile element have been devised. Conducted research resulted in obtaining the dependencies to determine stress intensity factor K and correction functions by which we can determine stress-strain state of metal Z-shaped cross section elements at each of the stages of development of cracks during bending. Using these dependencies enables us to determine operational life of frame structural elements and make suggestions for its improvement.

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МАТЕМАТИЧНА МОДЕЛЬ РОЗВИТКУ КРАЙОВОЇ ТРІЩИНИ ПРИ ЗГИНІ ТОНКОСТІННОГО Z-ПОДІБНОГО ПРОФІЛЮ

Тарас Довбуш; Микола Сташків; Надія Хомик; Наталія Рубінець

Тернопільський національний технічний університет імені Івана Пулюя, Тернопіль, Україна

***Резюме**. Розглянуто інженерні методи визначення коефіцієнтів інтенсивності напружень для дефектних елементів відкритого профілю при згині. Проаналізовано характерні стадії розвитку крайової тріщини Z-подібного профілю. Побудовано математичні моделі та виведено залежності для розрахунку коефіцієнтів інтенсивності напружень за двома методами через номінальні напруження у нетто-перетині та через зміну осьового моменту інерції поперечного перетину Z-подібного профілю. Досліджено докритичний ріст крайової тріщини, визначено сингулярність напружень в околі втомної тріщини – коефіцієнти інтенсивності напружень першого роду, враховуючи моделі В.В. Панасюка для розтягу і чистого згину. Аналітично визначено поправочні функції, які враховують зміну геометрії тонкостінних профілів при поширенні втомної тріщини, на основі яких записано коефіцієнти інтенсивності напружень для елементів тонкостінного профілю, які сприймають деформації розтягу і чистого згину. Побудовано графіки поправочних функцій. Провівши їх апроксимацію, отримано узагальнену поправочну функції Z-подібного профілю розмірами 200х87х6 mm, яка спрощує розрахунок залишкового ресурсу роботи елементів конструктивної системи.*

***Ключові слова**: коефіцієнт інтенсивності напружень, поправочна функція, довжина тріщини.*

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