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ANALYSIS OF BIMETALLIC BEAM WITH WEAK SHEAR CONNECTION

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Abstract: In this paper an analytical solution is presented to determine the deflection, slip and stresses in bimetallic beam with flexible shear connection. The thermal load is derived from uniform temperature change. The Euler-Bernoulli hypothesis is assumed to hold for each layer separately and a linear constitutive equation between the horizontal slip and the inter-laminar shear force is considered. An example illustrates the application of the developed analytical method.
Keywords: bimetallic beam, interlayer slip, shear connection, thermal load

INTRODUCTION

There exist several works on bimetallic elastic beams with perfect bond [1,2,3,4,5]. In this paper the bimetallic beam with weak shear connection under the action of uniform temperature change is studied. The present analytical method is based on the Euler-Bernoulli's beam theory and the one-dimensional version of the constitutive equation of linear thermoelasticity (Duhamel-Neumann's law). The considered bimetallic beam configuration is shown in Figure 1.

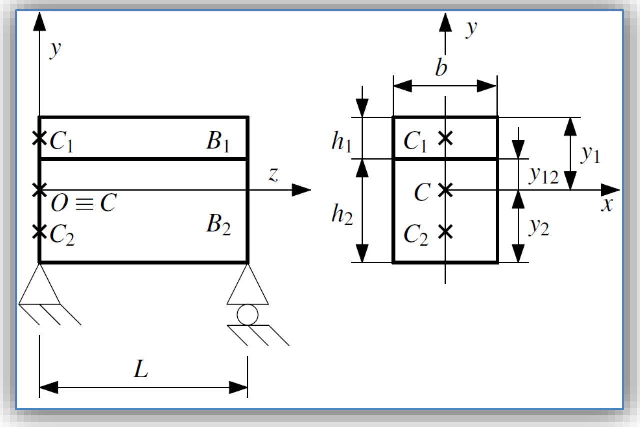

Figure 1. Simply supported bimetallic beam

The beam component B_i has the rectangular cross section A_i whose dimensions are h_i and b $(i=1,2)$. The modulus of elasticity for beam component B_i is E_i and the coefficients of linear thermal expansion is α_i $(i=1,2)$. The length of the simply supported bimetallic beam is L. The origin O of the rectangular Cartesian coordinate system $Oxyz$ is the E-weighted centre of the left end cross section, so that axis z is the E-weighted center-line of the bimetallic beam. A point P in $B=B_1\cup B_2$ is indicated by the position vector $\overrightarrow{OP}=\mathbf{r}=\mathbf{R}+z\mathbf{e}_z=x\mathbf{e}_x+y\mathbf{e}_y+z\mathbf{e}_z$, where $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ are the unit vectors of the coordinate system $Oxyz$. It is known that the position of E-weighted centre of the cross section $A=A_1\cup A_2$ is obtained from next equation [6]

$$E_1\int_{A_1}\mathbf{R}\,\mathrm{d}A+E_2\int_{A_2}\mathbf{R}\,\mathrm{d}A=\mathbf{0}. \tag{1}$$

For cross section shown in Figure 1 we have

$$c_1=\left|\overrightarrow{CC_1}\right|=\frac{A_2E_2}{\langle AE\rangle}c,\qquad c_2=-\left|\overrightarrow{CC_2}\right|=-\frac{A_1E_1}{\langle AE\rangle}c, \tag{2}$$

$$c=\left|\overrightarrow{C_2C_1}\right|=c_1-c_2=\frac{1}{2}\left(h_1+h_2\right), \tag{3}$$

$$\langle AE\rangle=A_1E_1+A_2E_2, \tag{4}$$

$$y_1=c_1+\frac{1}{2}h_1,\quad y_2=c_2-\frac{1}{2}h_2,\quad y_{12}=c_1-\frac{1}{2}h_1. \tag{5}$$

In Eqs. (2), (4) A_i denotes the cross sectional area of beam component B_i $(i=1,2)$ and the position of the common boundary of A_1 and A_2 is indicated by y_{12} (Figure 1).

GOVERNING EQUATION

According to the Euler-Bernoulli hypothesis (kinematic assumption) which is valid for each homogeneous beam components the deformed configuration is described by the displacement field [6]

$$\mathbf{u}=\mathbf{u}(x,y,z)=v(z)\mathbf{e}_y+\left(w_i(z)-y\frac{\mathrm{d}v}{\mathrm{d}z}\right)\mathbf{e}_z, \qquad (6)$$

where $(x,y,z)\in B_i$, $(i=1,2)$. Eq. (6) shows that the axial displacement of beam component B_i $(i=1,2)$ is separated into two parts: $w_i(z)$ $(i=1,2)$ describes the rigid translation of the cross section A_i $(i=1,2)$ at z and the second part of the axial displacement of A_i $(i=1,2)$ derived from the deflection of cross section [6]. On the common boundary of B_1 and B_2 the axial displacement has jump which is called the interlayer slip. According to Eq. (6) the interlayer slip $s=s(z)$ can be computed as

$$s(z)=w_1(z)-w_2(z). \qquad (7)$$

Application of the strain-displacement relationships of the linearized theory of elasticity gives

$$\varepsilon_x=\varepsilon_y=\gamma_{xy}=\gamma_{xz}=\gamma_{yz}=0,\quad (x,y,z)\in B_1\cup B_2, \qquad (8)$$

$$\varepsilon_z=\frac{\mathrm{d}w_i}{\mathrm{d}z}-y\frac{\mathrm{d}^2v}{\mathrm{d}z^2},\quad (x,y,z)\in B_i,\ (i=1,2). \qquad (9)$$

In Eqs. (8), (9) ε_x, ε_y, ε_z are the normal strains and γ_{xy}, γ_{xz}, γ_{yz} are the shearing strains. The normal stress σ_z is computed from the one-dimensional version of Duhamel-Neumann's law [3,4]

$$\sigma_z=E_i\left(\frac{\mathrm{d}w_i}{\mathrm{d}z}-y\frac{\mathrm{d}^2v}{\mathrm{d}z^2}-\alpha_iT\right),\quad (x,y,z)\in B_1\cup B_2. \qquad (10)$$

In Eq. (10) T denotes the temperature change. The temperature of the two-layer composite beam initially is the reference temperature. Its temperature is slowly raised to a constant uniform temperature, so that the temperature change is T. Following we define the next section forces and moments [6]

$$N_1=\int_{A_1}\sigma_z\mathrm{d}A=A_1E_1\left(\frac{\mathrm{d}w_1}{\mathrm{d}z}-c_1\frac{\mathrm{d}^2v}{\mathrm{d}z^2}-\alpha_1T\right), \qquad (11)$$

$$N_2=\int_{A_2}\sigma_z\mathrm{d}A=A_2E_2\left(\frac{\mathrm{d}w_2}{\mathrm{d}z}-c_2\frac{\mathrm{d}^2v}{\mathrm{d}z^2}-\alpha_2T\right), \qquad (12)$$

$$M_1=\int_{A_1}y\sigma_z\mathrm{d}A=A_1E_1c_1\left(\frac{\mathrm{d}w_1}{\mathrm{d}z}-\alpha_1T\right)-E_1I_1\frac{\mathrm{d}^2v}{\mathrm{d}z^2}, \qquad (13)$$

$$M_2=\int_{A_2}y\sigma_z\mathrm{d}A=A_2E_2c_2\left(\frac{\mathrm{d}w_2}{\mathrm{d}z}-\alpha_2T\right)-E_2I_2\frac{\mathrm{d}^2v}{\mathrm{d}z^2}, \qquad (14)$$

where

$$I_i=\int_{A_i}y^2\mathrm{d}A,\quad (i=1,2). \qquad (15)$$

Eqs. (11), (12), (13) and (14) show that the normal stresses acting on cross section A_i $(i=1,2)$ are equivalent to a force-couple system (N_i,M_i) $(i=1,2)$ at C. This force-couple system (N_i,M_i) $(i=1,2)$ is illustrated in Figure 2. The interlayer slip s is assumed to be a linear function of shear force Q transmitted between the two beam components, that is we have [7]

$$Q=ks, \qquad (16)$$

where k is a constant, it is called slip modulus. Units of Q and k are

$$[Q]=\frac{\text{force}}{\text{length}},\quad [k]=\frac{\text{force}}{(\text{length})^2}. \qquad (17)$$

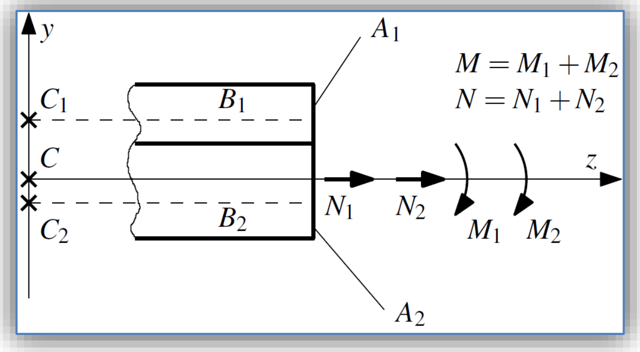

Figure 2. Normal forces and bending moments

In present problem there is no axial force $N=N_1+N_2$, that is

$$N=N_1+N_2=A_1E_1\frac{\mathrm{d}w_1}{\mathrm{d}z}+A_2E_2\frac{\mathrm{d}w_2}{\mathrm{d}z}-\langle AE\alpha\rangle T=0. \qquad (18)$$

Here,

$$\langle AE\alpha\rangle=A_1E_1\alpha_1+A_2E_2\alpha_2. \qquad (19)$$

From Eqs. (7) and (18) it follows that

$$\frac{\mathrm{d}w_1}{\mathrm{d}z}=\frac{A_2E_2}{\langle AE\rangle}\frac{\mathrm{d}s}{\mathrm{d}z}+\frac{\langle AE\alpha\rangle}{\langle AE\rangle}T, \qquad (20)$$

$$\frac{\mathrm{d}w_2}{\mathrm{d}z}=-\frac{A_1E_1}{\langle AE\rangle}\frac{\mathrm{d}s}{\mathrm{d}z}+\frac{\langle AE\alpha\rangle}{\langle AE\rangle}T. \qquad (21)$$

A simple computation based on Eqs. (11), (12) and Eqs. (20), (21) gives

$$N_1=\langle AE\rangle_{-1}\left[\frac{\mathrm{d}s}{\mathrm{d}z}-c\frac{\mathrm{d}^2v}{\mathrm{d}z^2}+(\alpha_2-\alpha_1)T\right], \qquad (22)$$

$$N_2=\langle AE\rangle_{-1}\left[-\frac{\mathrm{d}s}{\mathrm{d}z}+c\frac{\mathrm{d}^2v}{\mathrm{d}z^2}+(\alpha_1-\alpha_2)T\right], \qquad (23)$$

where

$$\langle AE\rangle_{-1}=\frac{1}{\dfrac{1}{A_1E_1}+\dfrac{1}{A_2E_2}}. \tag{24}$$

Application of the condition of equilibrium for forces in axial direction to beam component B_1 gives (Figure 3)

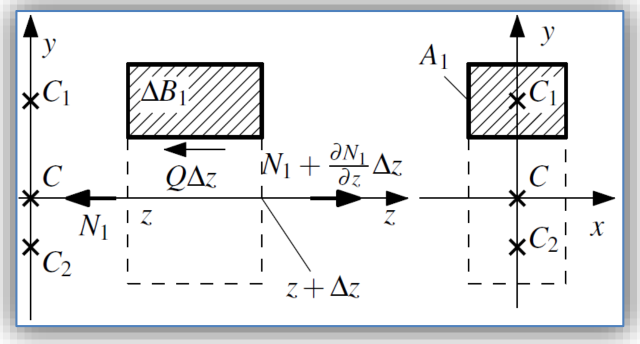

Figure 3. Equilibrium condition in z direction for a small beam element ΔB_1

$$\frac{\mathrm{d}N_1}{\mathrm{d}z}-ks=0. \tag{25}$$

Substitution of Eq. (22) into Eq. (25) yields

$$\frac{\mathrm{d}^2 s}{\mathrm{d}z^2}-c\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}-\frac{k}{\langle AE\rangle_{-1}}s=0. \tag{26}$$

It is evident the bending moment acting on the whole cross section $A=A_1\cup A_2$ is as follows

$$M=M_1+M_2= \\ =c\langle AE\rangle_{-1}\left[\frac{\mathrm{d}s}{\mathrm{d}z}+(\alpha_2-\alpha_1)T\right]-\{IE\}\frac{\mathrm{d}^2 v}{\mathrm{d}z^2}. \tag{27}$$

Here,

$$\{IE\}=I_1E_1+I_2E_2. \tag{28}$$

There is no applied mechanical load on the whole two-layer composite beam and at both supports there are not any reaction forces, so that

$$M(z)=0,\quad V(z)=\frac{\mathrm{d}M}{\mathrm{d}z}=0 \tag{29}$$

for all cross section. In Eq. $(29)_2$ $V=V(z)$ is the cross-sectional shear force. From Eq. $(29)_2$ we get

$$\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}=c\frac{\langle AE\rangle_{-1}}{\{IE\}}\frac{\mathrm{d}^2 s}{\mathrm{d}z^2}. \tag{30}$$

Combination of Eq. (26) with Eq. (30) gives

$$\frac{\mathrm{d}^2 s}{\mathrm{d}z^2}-\Omega^2 s=0, \tag{31}$$

where

$$\Omega^2=k\frac{\{IE\}}{\langle AE\rangle_{-1}\langle IE\rangle},\quad \langle IE\rangle=\{IE\}-c^2\langle AE\rangle_{-1}. \tag{32}$$

DETERMINATION OF THE SLIP AND DEFLECTION

For the simply supported bimetallic beam shown in Figure 1 the following boundary conditions are valid

$$v(0)=0,\quad v(L)=0, \tag{33}$$

$$N_1(0)=0,\quad N_1(L)=0. \tag{34}$$

The boundary conditions for bending moment $M=M(z)$

$$M(0)=0,\quad M(L)=0 \tag{35}$$

are satisfied according to Eq. (29). From the boundary conditions

$$N_1(0)=0,\quad M(0)=0 \tag{36}$$

and

$$N_1(L)=0,\quad M(L)=0 \tag{37}$$

it follows that

$$\frac{\mathrm{d}s}{\mathrm{d}z}=(\alpha_1-\alpha_2)T \tag{38}$$

is valid for $z=0$ and $z=L$. The general solution of the differential equation (31) can be represented as

$$s(z)=K_1\cosh\Omega z+K_2\sinh\Omega z. \tag{39}$$

Substitution of Eq. (39) into the boundary condition (38) leads to the next results

$$K_1=-T\frac{\alpha_1-\alpha_2}{\Omega}\tanh\frac{\Omega L}{2}, \tag{40}$$

$$K_2=T\frac{\alpha_1-\alpha_2}{\Omega}. \tag{41}$$

From Eqs. (27), $(29)_1$ and Eq. (39) it follows that

$$c\langle AE\rangle_{-1}\left[K_1(\cosh\Omega z-1)+K_2\sinh\Omega z+ \\ +(\alpha_2-\alpha_1)Tz\right]-\{IE\}\frac{\mathrm{d}v}{\mathrm{d}z}+\{IE\}K_3=0, \tag{42}$$

where

$$K_3=\left(\frac{\mathrm{d}v}{\mathrm{d}z}\right)_{z=0}. \tag{43}$$

Integrating of Eq. (42) gives

$$\{IE\}\left[v(z)-v(0)\right]=c\langle AE\rangle_{-1}\left[K_1\frac{\sinh\Omega z-\Omega z}{\Omega}+ \\ +K_2\frac{\cosh\Omega z-1}{\Omega}+\frac{\alpha_2-\alpha_1}{2}Tz^2\right]+\{IE\}K_3 z. \tag{44}$$

From boundary conditions (33) we obtain

$$K_3=-\frac{c\langle AE\rangle_{-1}}{\{IE\}}\left[K_1\frac{\sinh\Omega L-\Omega L}{\Omega L}+ \\ +K_2\frac{\cosh\Omega L-1}{\Omega L}+\frac{L}{2}(\alpha_2-\alpha_1)T\right]. \tag{45}$$

Substitution of Eq. (45) into Eq. (44) gives

$$v(z)=\frac{c\langle AE\rangle_{-1}}{\{IE\}}\left[K_1\left(\frac{\sinh\Omega z-\Omega z}{\Omega}-\frac{\sinh\Omega L-\Omega L}{\Omega L}z\right)+ \\ +K_2\left(\frac{\cosh\Omega z-1}{\Omega}-\frac{\cosh\Omega L-1}{\Omega L}z\right)- \\ -\frac{\alpha_2-\alpha_1}{2}T\left(Lz-z^2\right)\right]. \tag{46}$$

COMPUTATIONS OF THERMAL STRESSES

We assume that the state of stresses of bimetallic beam can be characterized by the following stresses $\sigma_z = \sigma_z(y,z)$, $\tau_{yz} = \tau_{yz}(y,z)$, $\sigma_y = \sigma_y(y,z)$. The normal stress σ_z is obtained from Eqs. (10) and (20) as

$$\sigma_z = E_1\left[\frac{c_1}{c}\frac{\mathrm{d}s}{\mathrm{d}z} - y\frac{\mathrm{d}^2 v}{\mathrm{d}z^2} + \frac{c_1}{c}(\alpha_2-\alpha_1)T\right], \quad (x,y,z)\in B_1, \tag{47}$$

$$\sigma_z = E_2\left[\frac{c_2}{c}\frac{\mathrm{d}s}{\mathrm{d}z} - y\frac{\mathrm{d}^2 v}{\mathrm{d}z^2} + \frac{c_2}{c}(\alpha_2-\alpha_1)T\right], \quad (x,y,z)\in B_2. \tag{48}$$

Shearing stresses $\tau_{yz} = \tau_{yz}(y,z)$ is computed by the use of equation of equilibrium

$$\frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} = 0, \quad (x,y,z)\in B_1\cup B_2. \tag{49}$$

A detailed computation yields the next result

$$\tau_{yz} = -E_2\left[(y-y_2)\frac{c_2}{c}\frac{\mathrm{d}^2 s}{\mathrm{d}z^2} - \frac{1}{2}\left(y^2-y_2^2\right)\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}\right], \tag{50}$$
$$(x,y,z)\in B_2,$$

$$\tau_{yz} = -E_2\left[(y_{12}-y_2)\frac{c_2}{c}\frac{\mathrm{d}^2 s}{\mathrm{d}z^2} - \frac{1}{2}\left(y_{12}^2-y_2^2\right)\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}\right] - E_1\left[(y-y_{12})\frac{c_1}{c}\frac{\mathrm{d}^2 s}{\mathrm{d}z^2} - \frac{1}{2}\left(y^2-y_{12}^2\right)\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}\right], \tag{51}$$
$$(x,y,z)\in B_1.$$

Here, the stress boundary condition

$$\tau_{yz}(y_2,z) = 0 \tag{52}$$

and the continuity condition of τ_{yz} at $y = y_{12}$

$$\lim_{\varepsilon\to 0}\left[\tau_{yz}(y_{12}-\varepsilon,z) - \tau_{yz}(y_{12}+\varepsilon,z)\right] = 0 \tag{53}$$

are used. To obtain the normal stress $\sigma_y = \sigma_y(y,z)$ we consider the next equation of mechanical equilibrium

$$\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} = 0. \tag{54}$$

Integration of Eq. (54) gives

$$\sigma_y = E_2\left[\left(\frac{y^2+y_2^2}{2} - yy_2\right)\frac{c_2}{c}\frac{\mathrm{d}^3 s}{\mathrm{d}z^3} - \frac{1}{2}\left(\frac{y^3+2y_2^3}{3} - y_2^2 y\right)\frac{\mathrm{d}^4 v}{\mathrm{d}z^4}\right], \quad (x,y,z,)\in B_2, \tag{55}$$

$$\sigma_y = E_2\left[\left(\frac{y_{12}^2+y_2^2}{2} - y_{12}y_2\right)\frac{c_2}{c}\frac{\mathrm{d}^3 s}{\mathrm{d}z^3} - \frac{1}{2}\left(\frac{y_{12}^3+2y_2^3}{3} - y_2^2 y_{12}\right)\frac{\mathrm{d}^4 v}{\mathrm{d}z^4}\right] + E_1\left[\left(\frac{y^2+y_{12}^2}{2} - yy_{12}\right)\frac{c_1}{c}\frac{\mathrm{d}^3 s}{\mathrm{d}z^3} - \frac{1}{2}\left(\frac{y^3+2y_{12}^3}{3} - y_{12}^2 y\right)\frac{\mathrm{d}^4 v}{\mathrm{d}z^4}\right] - (y-y_{12})\left(\frac{\partial \tau_{yz}}{\partial z}\right)_{y=y_{12}}, \tag{56}$$
$$(x,y,z)\in B_1.$$

Here, we use the stress boundary condition

$$\sigma_y(y_2,z) = 0, \tag{57}$$

and stress continuity condition of σ_y at $y = y_{12}$

$$\lim_{\varepsilon\to 0}\left[\sigma_y(y_{12}-\varepsilon,z) - \sigma_y(y_{12}+\varepsilon,z)\right] = 0. \tag{58}$$

Integration of Eq. (49) leads to next equation

$$\tau_{yz}(y_1,z) - \tau_{yz}(y_2,z) + \frac{\partial}{\partial z}\int_{y_2}^{y_1}\sigma_z \mathrm{d}y = 0, \tag{59}$$

that is

$$\tau_{yz}(y_1,z) = -\frac{1}{b}\frac{\partial N}{\partial z} = 0. \tag{60}$$

By the same method from Eq. (54) we obtain

$$\sigma_y(y_1,z) - \sigma_y(y_2,z) + \frac{\partial}{\partial z}\int_{y_2}^{y_1}\tau_{yz}\mathrm{d}y = 0, \tag{61}$$

that is

$$\sigma_y(y_1,z) = -\frac{1}{b}\frac{\partial V}{\partial z} = 0. \tag{62}$$

Eqs. (60) and (62) show that the stress boundary conditions for τ_{yz} and σ_y at $y = y_1$ are satisfied. In the following we prove that

$$\tau_{yz}(y_{12},z) = \frac{Q(z)}{b} = \frac{ks(z)}{b}. \tag{63}$$

Starting from Eq. (50) we can write

$$\begin{aligned}\tau_{yz}(y_{12},z) &= -E_2\left[(y_{12}-y_2)\frac{c_2}{c}\frac{\mathrm{d}^2 s}{\mathrm{d}z^2} - \frac{1}{2}\left(y_{12}^2-y_2^2\right)\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}\right] = \\ &= -E_2\left[\frac{c_2 h_2}{c}\frac{\mathrm{d}^2 s}{\mathrm{d}z^2} - c_2 h_2\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}\right] = \\ &= -\frac{E_2 A_2}{b}\frac{c_2}{c}\left[\frac{\mathrm{d}^2 s}{\mathrm{d}z^2} - c\frac{\mathrm{d}^3 v}{\mathrm{d}z^3}\right] = -\frac{E_2 A_2}{b}\frac{c_2}{c}\frac{k}{\langle AE\rangle_{-1}}s(z) = \\ &= \frac{E_1 A_1 E_2 A_2}{\langle AE\rangle\langle AE\rangle_{-1}}\frac{Q(z)}{b} = \frac{Q(z)}{b}\end{aligned} \tag{64}$$

according to Eq. (63). Here, Eqs. (2,3,4,5) and Eqs. (26), (50) have been used to prove the validity of Eq. (64).

NUMERICAL EXAMPLE

The following data are used in the numerical example (Figure 1):

$$b = 0.03\ \text{m},\ h_1 = 0.01\ \text{m},\ h_2 = 0.03\ \text{m},\ E_1 = 1.22\times 10^{11}\ \text{Pa},$$
$$E_2 = 8\times 10^{10}\ \text{Pa},\ L = 1.5\ \text{m},\ \alpha_1 = 2.8\times 10^{-6}\ 1/\text{K},$$
$$\alpha_2 = 1.43\times 10^{-5}\ 1/\text{K},\ T = 200\ \text{K},\ k = 60\times 10^{6}\ \text{Pa}.$$

Figure 4 shows the graph of deflection function and the graph of slip function is illustrated in Figure 5. The stresses $\sigma_z = \sigma_z(y,z)$, $\tau_{yz} = \tau_{yz}(y,z)$ and $\sigma_y = \sigma_y(y,z)$ for some cross section ($z = L/4$, $z = L/3$, $z = L/2$) are shown in Figures 6, 7 and 8.

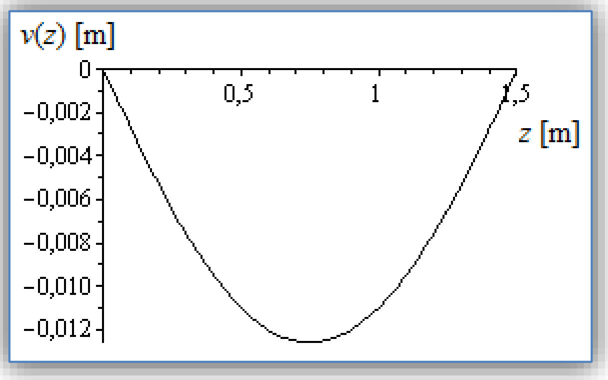

Figure 4. The graph of $v = v(z)$

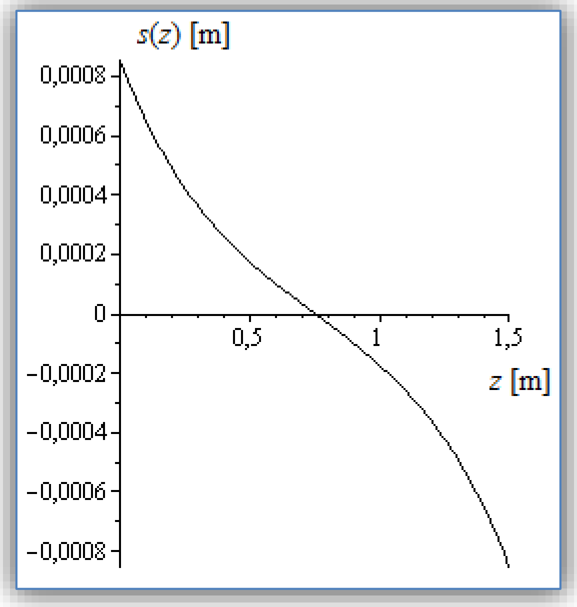

Figure 5. The graph of $s = s(z)$

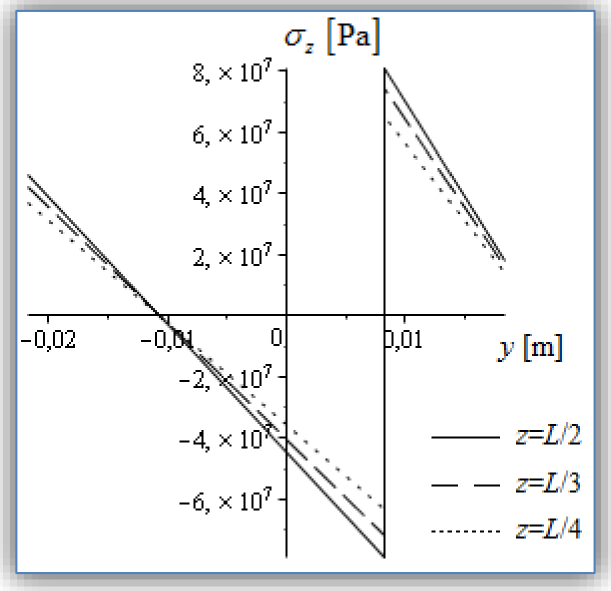

Figure 6. Plots of $\sigma_z = \sigma_z(y,z)$

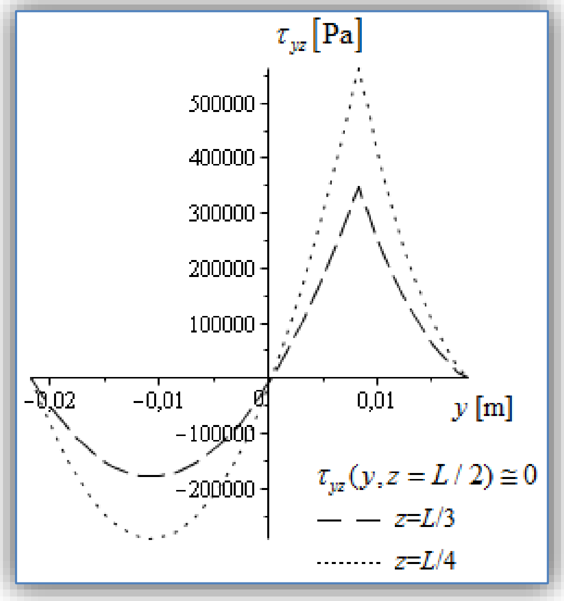

Figure 7. Plots of $\tau_{yz} = \tau_{yz}(y,z)$

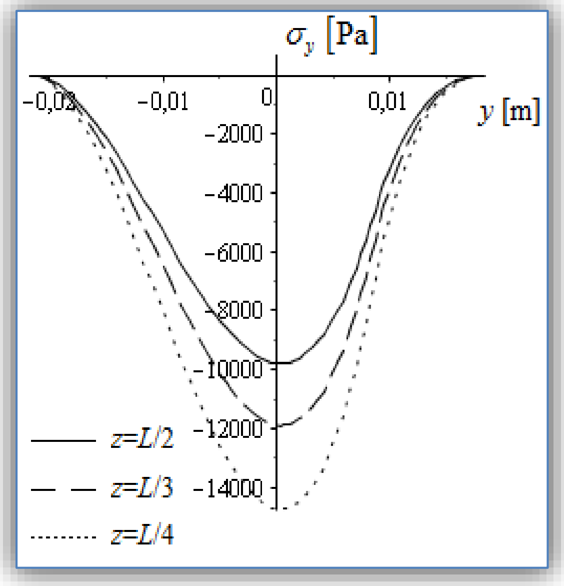

Figure 8. Plots of $\sigma_y = \sigma_y(y,z)$

CONCLUSIONS

In this paper the elastic bimetallic beam with flexible shear connection is analyzed. The applied thermal load is caused by a uniform temperature change.

An analytical method, which is based on slip-deflection formulation, is proposed to get the displacements and stresses.

A numerical example illustrates the application of method developed. Numerical solutions derived by this analytical method can be used as benchmark solutions for solutions obtained by other methods.

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