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RELATIONSHIP BETWEEN THE GEOMETRY OF THE TRANSITION SECTION AND THE LOADS ACTING ON THE CONVEYOR BELT

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Abstract: This article presents a universal theoretical model of the belt in the transition section of a troughed conveyor, for a steel-cord belt which is divided into cables and layers of rubber, and for a textile belt which is divided into narrow strips. It describes geometrical forces in the transition section of the belt and offers an illustrative analysis of loads acting on the belt. The analysis addresses the influence of the belt type on the non-uniform character of loads in the transition section of the conveyor. It focuses on how the non-uniformity of loads acting on the belt is affected by the length of the transition section, the trough angle, the belt width, and the height difference between the contour of the pulley coat and the coat of the middle idler in the trough. It presents optimal values of the pulley height with respect to the middle idler in the trough, which mitigate this non-uniformity. The use of a belt type different than the original type has been found to affect the belt load non-uniformity in the transition section of the conveyor.

***Keywords*:** *conveyor belt, transition section of the troughed conveyor, load state*

1. INTRODUCTION

The conveyor belt is an element which has a decisive influence on the effective and reliable operation of a belt conveyor and significantly influences the transportation costs (Hardygóra et al. 1999). Belt strength and elasticity are among the basic parameters considered when selecting a conveyor belt for a particular transportation task. An

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informed selection is expected to ensure that the forces acting on the operating belt will not cause it to break.

The most important fragment of the conveyor route is in the transition section, where the troughed belt assumes a flat shape when entering the pulley. This change modifies the stress state across the belt width. The outermost load-carrying elements of the core accept additional tensile loads while the loads in the central part of the belt decrease. In this phase, the geometry of the transition section should be adjusted in order to limit this non-uniformity of the loads acting on the belt, to prevent it from breaking and to limit the loss of its stability due to excessively low forces in its central part. The above fact applies particularly to the transition section of the conveyor, in which the belt experiences the greatest forces, as is most frequently the case at the point where the belt enters the drive pulley and as a result changes its shape from troughed to flat. The geometrical parameters of the transition section have an influence also on the discharge trajectory of the transported material and on the design of the transfer stations (Doroszuk and Król 2019).

When implementing a particular transportation task, the force levels in the belt and the power of the drive system are identified after calculating conveyor resistances to motion and the minimal tensile force required to ensure a frictive engagement between the pulley and the belt. Köken et al. (2021) reviewed and compared the leading methods used in belt conveyor calculations.

In the existing calculation methods, the length of the transition section should be defined in such a manner that the non-uniformity of belt loads is reduced and unit forces in the belt are not exceeded. The CEMA5 method (2002) defines the minimum length of the transition section depending on the geometrical parameters of the section and differentiates between only two groups of belts: with steel cords and with textile core. Importantly, however, textile core belts may significantly differ with respect to their elastic properties and show different reactions in response to the geometry changes of the transition section. The Fenner-Dunlop method has a similar approach to the identification of the transition section (2009). In the DIN 22101 method (2011), the length of the transition section is calculated on the basis of simplified relationships, but with allowance for the longitudinal elastic modulus of the belt.

Accurate identification of the stress state in the belt along the transition section requires a model which allows for not only the longitudinal elastic modulus of the belt but also for the interactions between the adjacent cables or strips in the belt. Oehmen (1979) and Hager and Tappeiner (1993) focused in their research on identifying the strain state in the belt along the transition section. Schmandra (1991) presented a general theoretical model of a steel-cord belt allowing for the interactions between the adjacent cables. The literature also mentions implementations of the finite element method in the modeling of a belt along the transition section of the conveyor (Harrison (1998); Fedorko and Ivančo 2012; Fedorko et al. 2015). Fedorko et al. (2015) used the finite element method to analyze the influence of the elastic modulus in the longitudinal and transverse directions of the belt on belt load non-uniformity.

This article describes a universal theoretical model of the belt in the transition section of the conveyor for two cases. The first case is a steel-cord belt, divided into cables and layers of rubber, and the second case is a textile belt with a textile core divided into narrow strips. It also presents the laboratory-tested properties of the belts used in the theoretical model. An analysis was performed into how the non-uniformity of belt load along the transition section of the conveyor will change if belts with different cores are used. The analyses also involved the influence of the geometry of the transition section on belt load non-uniformity.

2. MODEL OF THE BELT IN THE TRANSITION SECTION OF THE CONVEYOR

2.1. PRELIMINARY ASSUMPTIONS BEHIND THE MODEL

1. The belt is considered as a multi-strip flat tension member, globally carrying only longitudinal loads. In the case of a steel-cord belt, the strip is a steel cable with the surrounding rubber, and in the case of a textile belt, the strip is composed of a number of warp threads.
2. The strips are modeled as linear elastic elements.
3. The rubber which connects the adjacent cables or weft threads is responsible for the mutual interaction of the adjacent strips, which is modeled with the use of the artificial modulus of non-dilatational strain.
4. The longitudinal rigidity of the strips and the artificial modulus of non-dilatational strain between the strips are determined on the basis of laboratory tests.
5. The considered belt section has a length $L_e + K$, where L_e is the length of the transition section, and K is the length of the section of influence, in which the stresses equalize.
6. The belt is subjected to tension at a constant force F_N.
7. No external loads are observed along the length L_e of the transition section (i.e., motion resistances are absent and the impact of gravity is negligible), which means that in each cross-section the sum of forces in the strips is equal to the tensile force F_N. The influence of the pulley is also negligible.
8. The rubber between the cables is not deformed in lateral direction, and therefore the distances between the cable axes (the cable pitch) are constant. This assumption allows the equation to be solved as a system of coplanar forces.
9. Calculations are performed for a half of the belt, from the edge to its axis of symmetry (the system is assumed to be symmetrical).

2.2. GEOMETRICAL FORCES IN THE TRANSITION SECTION OF THE CONVEYOR

The basis for a model thus formulated is to determine elongations for individual strips. These result from the path traveled by each strip when the belt transitions from a troughed cross-section into a flat cross-section on the pulley. Consideration is here paid to the path traveled by steel cables (in the case of steel-cord belts) or to the path of the longitudinal axes of the analyzed strips (in the case of textile belts). The issue is analytically described with the use of the coordinate system shown in Fig. 1.

The length of each cable Δl (each longitudinal axis of the strip) is determined as the Euclidean distance between the position of the cable at the beginning of the coordinate system ($x = 0$) and the position of the cable at the end of the transition section ($x = L_e$).

$$\Delta l = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}\ . \tag{1}$$

Cable elongation Δu in the transition section is:

$$\Delta u = \Delta l - L_e. \tag{2}$$

At the beginning of the transition section, the belt cross-section is troughed, and the coordinate ($x = 0$). The positions of individual cables may be described with the following relationships:

– for $z \le \frac{1}{2} b_m$:

$$z_i = i \cdot t, \tag{3}$$

$$y_i = 0; \tag{4}$$

– for $z > \frac{1}{2} b_m$:

$$z_i > \frac{1}{2} b_m + \left(i \cdot t - \frac{1}{2} b_m \right) \cos\alpha, \tag{5}$$

$$y_i = \left(z_i - \frac{1}{2} b_m \right) \tan\alpha, \tag{6}$$

where:

i – cable number, $i = 1 \div n$,
n – number of cables across the half of the belt width,
b_m – width of the central part of the belt trough,
t – cable pitch (strip width),
α – trough angle.

At the end of the transition section, the belt cross-section is flat, and the coordinate ($x = L_e$). The positions of individual cables may be described with the following relationships:

$$z_i = i \cdot t, \tag{7}$$

$$y_i = e, \tag{8}$$

where e – height difference between the contour of the pulley coat and the central part of the trough

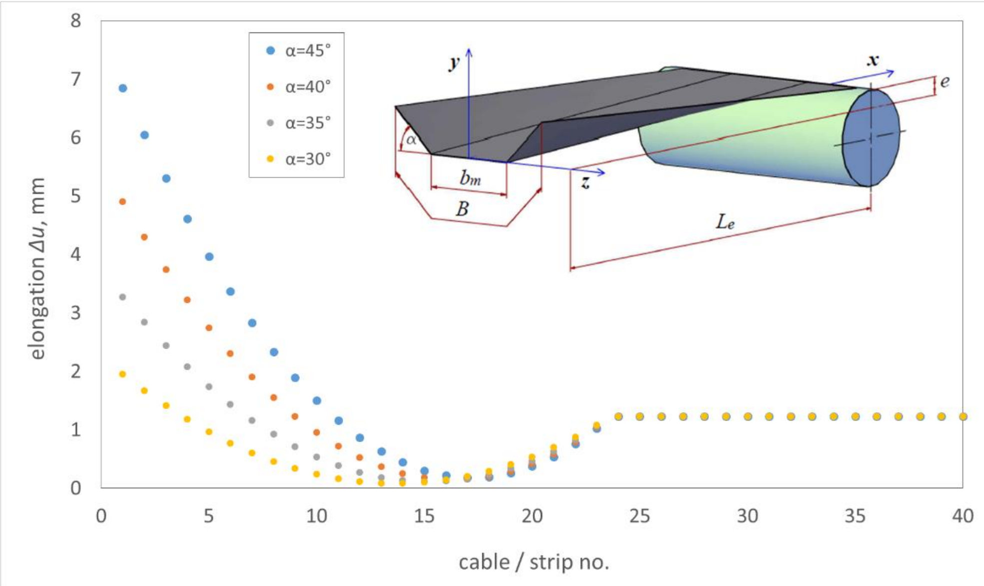

Fig. 1. Cable/strip elongation in the transition section of the belt conveyor identified from the geometrical model: L_e – length of the transition section, B – belt width, α – trough angle, b_m – width of the central part of the belt trough, e – height difference between the contour of the pulley coat and the central part of the trough (L_e = 2.6 m, B = 1.2 m, e = 0.08 m)

The belt displacement area determined from the model based only on the geometrical relationships (Fig. 1) is a certain simplification of the actual condition, but it is sufficient to analyze the behavior of various belt core structures along the transition section of the conveyor.

2.3. THEORETICAL BASIS FOR THE BELT MODEL IN THE TRANSITION SECTION

The model reflects half of the belt having a length equal to the length of the transition section L_e and the length of the section of influence K. The symmetrical half of the belt core is composed of n cables. The initial load state in the belt core is due to the F_N force in the belt. The cables form a parallel structure, i.e., each cable in the core will be elongated by an identical initial distance u_o. Thus the initial force in the i-th cable F_{oi} is:

$$F_{oi} = \frac{u_o}{l}(EA)_i \tag{9}$$

from the condition of the equilibrium of forces:

$$F_N = 2\sum_{i=1}^{n} F_{oi}, \tag{10}$$

where:

$(EA)_i$ – longitudinal rigidity of the i-th cable/strip,

l – length of the analyzed belt section.

On the other hand, the forces from the geometrical input related to the transition section of the conveyor, in which cable elongations have a non-uniform distribution (Fig. 2), were identified on the basis of the elastic strain energy of a coplanar system of parallel cables and rubber (Woźniak 1998; Gładysiewicz and Woźniak 1998; Woźniak and Hardygóra 2021).

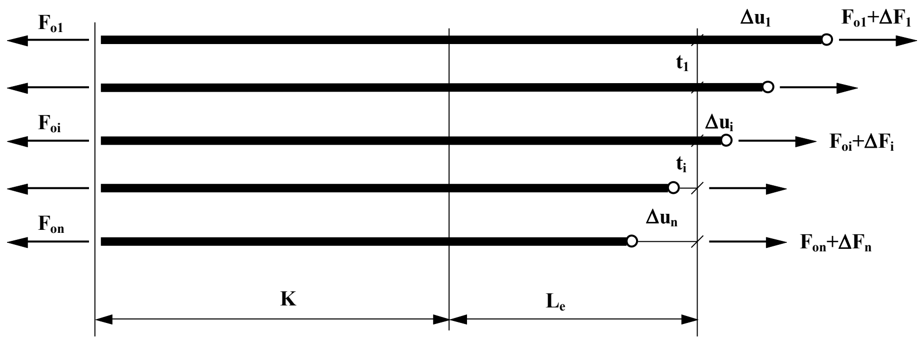

Fig. 2. Schematic diagram of loads acting on cables in the transition section

An increase in the elastic strain energy ΔE is accounted for by an increase of the elastic strain energy in the cable ΔE_l and by an increase of the elastic strain energy in the rubber ΔE_g.

$$\Delta E = \Delta E_l + \Delta E_g. \tag{11}$$

Partial derivative of energy with respect to force gives elongation

$$\frac{\partial \Delta E}{\partial \Delta F} = \Delta u. \tag{12}$$

The analysis of steel-cord belt models (Schmandra 1991) indicates that differential equations describing the variability of forces in the cables should be solved by combining hyperbolic functions, which is the effect of the character of differential equations. The development of these functions into Taylor series gives polynomials with strongly decreasing successive terms.

Only the first two terms may be accepted with a satisfactory accuracy of several percent (Gładysiewicz 2003), and therefore the equation describing the variability of forces in a single cable may be simplified to a quadratic function. This assumption is confirmed by the results of load tests performed for cables in the areas of the transition sections (Hager and Tappeiner 1993). Due to the interaction between adjacent cables through the rubber layer (and in the case of textile belts, through the rubber and the weft threads) the force in any cable changes in accordance with the following relationship:

$$F(x) = F_o(1 + ax^2) \tag{13}$$

for $x = L_e + K = L$

$$F_k = F_o(1 + aL^2), \tag{14}$$

where:

F_o – initial force,

F_k – final force.

Thus

$$a = \frac{1}{L^2}\left(\frac{F_k}{F_o} - 1\right), \tag{15}$$

then

$$F(x) = F_o + F_k\frac{x^2}{L^2} - F_o\frac{x^2}{L^2}. \tag{16}$$

Increase of elastic strain energy in the cable is expressed with equation

$$\Delta E_l = \frac{1}{2(EA)}\int_0^L F^2(x)dx = \frac{1}{2(EA)}F_o^2\int_0^L (1 + ax^2)^2 dx, \tag{17}$$

$$\Delta E_l = \frac{1}{2(EA)}F_o^2\left(L + \frac{2}{3}aL^3 + \frac{1}{5}a^2L^5\right), \tag{18}$$

then the partial derivative of elastic strain energy in the cable with respect to force is:

$$\frac{\partial \Delta E_l}{\partial F_k} = \frac{\partial \Delta E_l}{\partial a} \cdot \frac{\partial a}{\partial F_k}, \tag{19}$$

$$\frac{\partial \Delta E_l}{\partial F_k} = \frac{L}{(EA)} \left(\frac{3}{15} F_k + \frac{2}{15} F_o \right). \tag{20}$$

The next step consists in determining elastic strain energy and derivative for the strip of rubber between the cables.

$$dE_g = \frac{1}{2} \Delta u(x) \tau h_t \cdot dx, \tag{21}$$

h_t – belt thickness.
Tangential stresses τ are:

$$\tau = \gamma G^* = \frac{\Delta u(x)}{t} G^*, \tag{22}$$

where:
G^* – artificial modulus of non-dilatational strain determined in laboratory tests,
t – cable pitch.
Then

$$dE_g = \frac{1}{2} \cdot \frac{h_t G^*}{t} \int_0^x \Delta u(x)^2 \, dx. \tag{23}$$

Partial derivative of the energy in the *i*-th rubber strip with respect to the force in the *i*-th cable is

$$\frac{\partial \Delta E_{gi}}{\partial F_i} = \frac{h_t G^*}{t} \int_0^x \Delta u(x) \cdot \frac{\partial \Delta u(x)}{\partial F_i} \, dx. \tag{24}$$

Partial derivative of energy with respect to force for the *i*-th cable is

$$\frac{\partial \Delta E_i}{\partial F_i} = \frac{\partial \Delta E_{li}}{\partial F_i} + \frac{\partial \Delta E_{gi}}{\partial F_i} + \frac{\partial \Delta E_{i-1}}{\partial F_i}. \tag{25}$$

Relationships (20), (24), (12) provide a system of *n* equations of the type:

$$A_{i-1} \cdot F_{i-1} + A_i \cdot F_i + A_{i+1} \cdot F_{i+1} + C_i = 0. \tag{26}$$

The matrix Gauss method allows a solution to the system of equations in the form of the vector of forces F_i in the cables.

3. TEST OBJECTS AND THEIR PROPERTIES

The analysis involved five conveyor belts with an identical nominal strength of 2000 kN/m, but with different core structure. The analyzed belts included a steel-cord belt, an aramid core belt, a solid woven PWG belt, and two multiply belts: a polyester-polyamide EP belt and a polyamide PP belt. The variability of the stress state across the belt in the transition section depends not only on the geometry of the system but also on the elastic properties of the belt. For long conveyors and for two-parameter belt models, the dynamic modulus is assumed to be equal to the longitudinal modulus of elasticity. The longitudinal modulus of elasticity E and the artificial modulus of non-dilatational strain G^* for the analyzed belts were identified at the Belt Conveying Laboratory, Wrocław University of Science and Technology. The modulus of elasticity E was tested in accordance with the method described in ISO 9856. On the other hand, the non-dilatational strain modulus G^* was tested with the use of an own test method. The method consists in the cyclical excitation of identical shear stresses along the adjacent steel cables or the adjacent strips (in the case of textile core belts) and in recording the obtained displacements. In the case of steel-cord belts, the test specimen was identical to the specimen required in the standard test of tearing the cable out of the rubber as per ISO 7623. In the case of textile core belts, the test specimens were separated into three strips 15 mm in width, with the shear stresses excited between the strips (see Fig. 3). Belts of an identical strength type but of a different core structure have significantly different elastic properties. The test results are shown in Table 1.

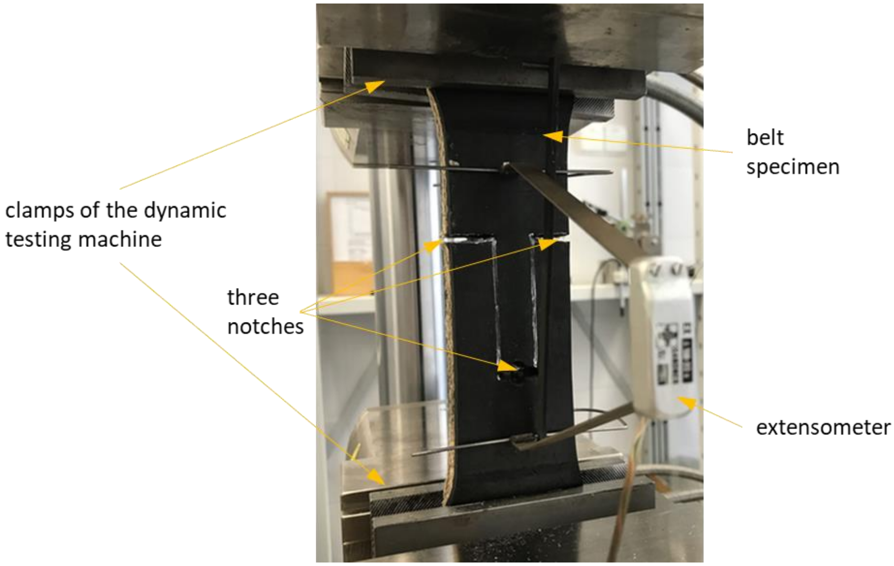

Fig. 3. Tests of non-dilatational strain modulus for textile core belts

Table 1. Elastic properties of the conveyor belts (2000 kN/m)

Belt type	*E* [N/m]	G^* [N/mm^2]
Steel-cord conveyor belt	112×10^6	7.5
Aramid conveyor belt	63×10^6	10.4
Solid woven conveyor belt	24×10^6	13.7
Multi-ply conveyor belt (EP)	19×10^6	9.0
Multi-ply conveyor belt (PP)	12×10^6	8.0

4. ANALYSIS OF THE LOAD ON THE BELT IN THE TRANSITION SECTION OF THE CONVEYOR

The calculations provided the distribution of loads on the cables/strips with respect to the belt width in the region of the pulley. Figure 4 shows force increments in the belt cables/strips in the cross-section of the area where the belt enters the pulley, the increments being the effect of deformations in the transition section. The graph includes half of the belt thickness, from the edge to the center.

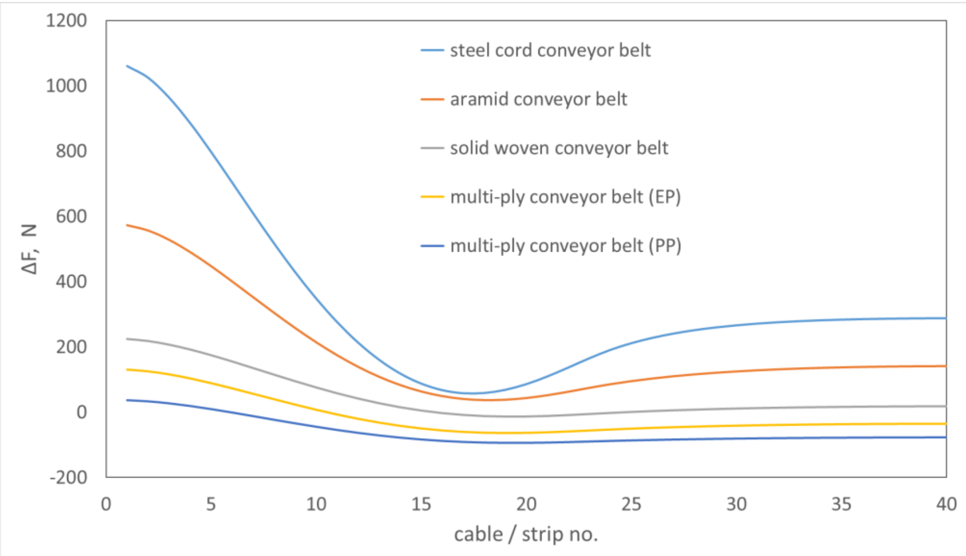

Fig. 4. Load increment in the belt in the transition section of the belt conveyor (L_e = 2.6 m, B = 1.2 m, e = 0.08 m, α = 40°)

In the analyzed cases, the absolute values of forces in individual belts are not important, as they result from the geometrical parameters of the transition section and its influence zone, as well as from the initial force in the belt, as assumed in the calculations. The behavior of different belts in the transition section can be reliably evaluated by observing the non-uniform character of loads acting on individual cables/strips in the belt. This non-uniform character of loads can be measured as a difference between the maximum and the minimum increment of force in the belt $\Delta F_{max} - \Delta F_{min}$. The load non-uniformity indicators thus obtained are shown in Table 2.

Table 2. Load non-uniformity indicators in the transition section

Belt type	$\Delta F_{max} - \Delta F_{min}$ [N]
Steel-cord conveyor belt	1003
Aramid conveyor belt	536
Solid woven conveyor belt	237
Multi-ply conveyor belt (EP)	194
Multi-ply conveyor belt (PP)	130

The resulting load non-uniformity indicators are significantly different for the analyzed belts. Importantly, however, when replacing a worn belt, each decision to change the belt type should be preceded by an analysis aiding the selection of the geometrical parameters of the transition section in the belt conveyor. This is of particular importance in the location where the greatest longitudinal forces are observed in the belt, i.e., typically in the drive pulley.

5. INFLUENCE OF MODIFIED GEOMETRIC PARAMETERS OF THE TRANSITION SECTION ON THE BELT LOAD

The analysis focused on how the length of the transition section, the trough angle (α), the belt width (B), and the height difference between the contour of the pulley coat and the coat of the middle idler in the trough (e) influence the non-uniformity of loads acting on the belt.

The calculations were performed for selected conveyor belts, by gradually increasing the length of the transition section (L_e) and by analyzing the changes in the non-uniformity of the belt load. The results of these calculations are shown in Fig. 5. If the non-uniformity level for loads on the multi-ply conveyor belt (PP) having the original length of the transition section L_e = 2.6 m is assumed as the target level, then the length of the transition section for the EP belt should be increased by 0.5 m, for the "solid woven" belt – by 0.8 m, for the aramid belt – by 2 m, and for the steel-cord belt – by 3.4 m.

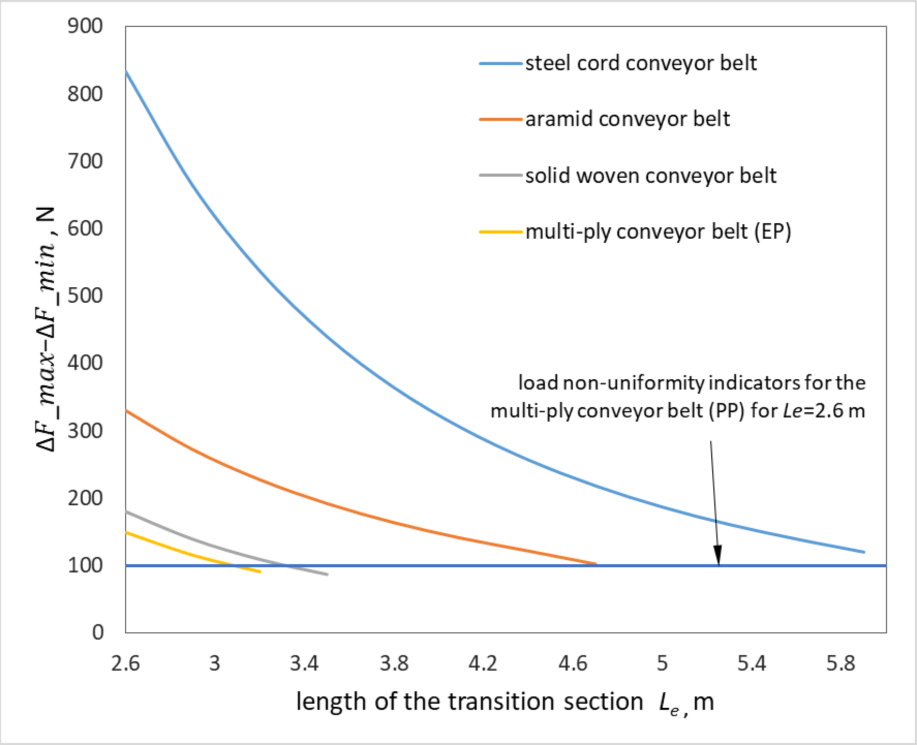

Fig. 5. The influence of the length of the transition section
on the non-uniform character of loads
(B =1.2 m, e = 0.09 m, α = 40°)

The analysis has also focused on how the height difference between the contour of the pulley coat and the coat of the middle idler in the trough (the dimension *e* in Fig. 1) affects the belt load non-uniformity. The calculations were performed for the solid woven conveyor belt and for different trough angles. The results are shown in Fig. 6. It presents optimal values of the pulley height with respect to the middle idler in the trough, which mitigate this non-uniformity. An increase of the trough angle results in the increased non-uniformity of the loads acting on the belt. It also increases the height of the pulley for which the belt load non-uniformity is the lowest.

Similar calculations were performed for the case in which the trough angle was constant (α = 35°) and the belt width was modified. The results are shown in Fig. 7. It presents optimal values of the pulley height with respect to the middle idler in the trough, which mitigate this non-uniformity. An increase of the belt width results in the increased non-uniformity of the loads acting on the belt. It also increases the height of the pulley for which the belt load non-uniformity is the lowest.

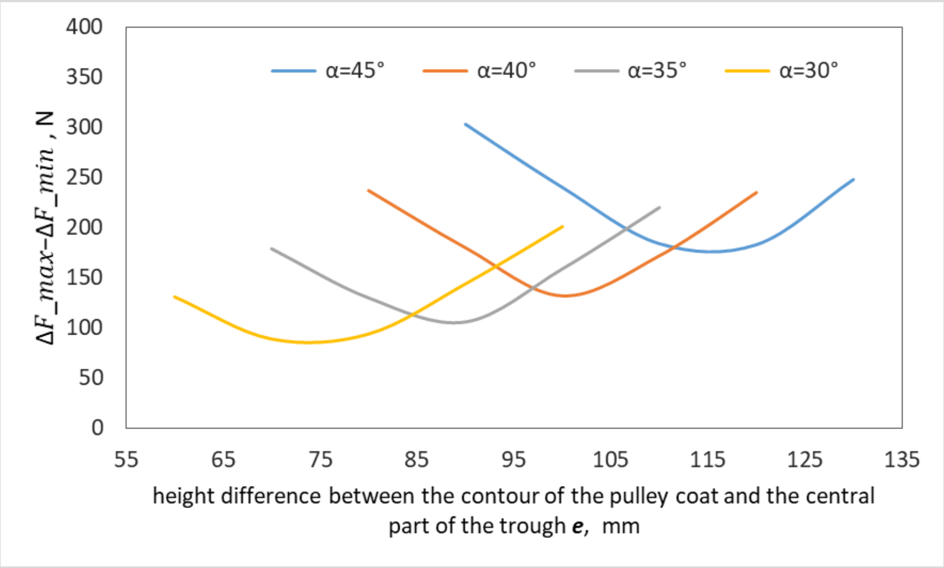

Fig. 6. The influence of the pulley position and trough angle
on the non-uniform character of loads
(B = 1.2 m, L_e = 2.6 m)

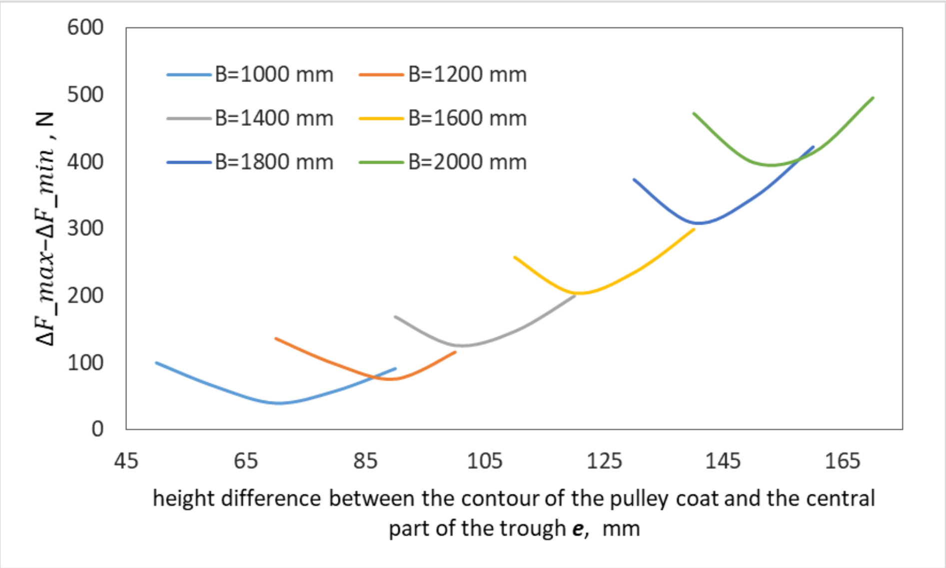

Fig. 7. Influence of pulley position and belt width
on the non-uniform character of loads (L_e = 3.0 m, α = 35°)

6. CONCLUSIONS

The transition section of the conveyor is a region in which the forces in the belt cross--section vary significantly. Such non-uniformity of belt loads was confirmed in the analysis performed with the use of an original theoretical model of the belt in the transition section of the troughed conveyor, which allows for the elastic properties of the belt and for the interaction with adjacent cables/strips. A comparison of the obtained results with the FEM test results obtained by other authors (Fedorko et al. 2015) indicates significant similarity of the stress patterns across the belt width.

Laboratory tests of the belts with an identical strength but a different core structure have demonstrated significantly different elastic properties. In the case when the operator decides to install a belt having different elastic properties but without modifying the geometrical parameters of the transition section, the belt load non-uniformity may be increased by as much as several hundred percent. This fact is of special importance in the case of the transition section in front of the drive pulley, where typically the highest force levels are observed in the belt.

The length of the transition section significantly affects the non-uniformity level of loads acting on the belt. The higher the longitudinal modulus of elasticity of the belt, the longer the transition section should be designed. Thus, the transition sections will be the shortest in the case of polyamide belts, and the longest in the case of steel-cord belts.

The height of the pulley also affects the non-uniformity of the belt loads in the transition section. An optimal pulley position exists in which the non-uniformity is the lowest. This position depends on the belt width and on the trough angle of the idler sets. An increase of the trough angle or of the belt width should also result in an increased pulley height relative to the position of the middle idler in the trough. In practice, the discharge conditions and trajectory of the transported material also should be considered when setting the height of the pulley.

An increase of the trough angle or of the belt width increases the non-uniformity of the loads acting on the belt in the transition section of the conveyor.

Further research is planned to involve tests of the properties of conveyor belts having different geometries and core structures and the implementation of FEM in the modeling of the transition section of the belt conveyor.

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