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EXPERIMENTAL RESEARCH AND MATHEMATICAL MODELLING AS AN EFFECTIVE TOOL OF ASSESSING FAILURE OF CONVEYOR BELTS

BADANIA EKSPERYMENTALNE I MODELOWANIE MATEMATYCZNE JAKO SKUTECZNE NARZĘDZIA OCENY USZKODZEŃ TAŚM PRZENOŚNIKOWYCH

One of the main causes of damage is their dynamic stress, which often ends the life-cycle caused end of conveyor belts. Dynamic stress leads to fatigue strength functions in shear loading of fabric conveyor belts. Damage of the conveyor belt can be solved by extensive experimental research in laboratory conditions on complex equipments made just for this purpose. The aim of the study is to determine the relation of power in the conveyor belt to the weight of the material which is falling onto a conveyor belt and to impact level height, which is based on data obtained in the experimental research. The experimental measurements have been performed on a test rig, which was developed at the Institute of Logistics and Transport Industry FBERG of Kosice. Results of mathematical modelling clearly say that proposed regression models describe real behaviour of the conveyor belts in productions during their dynamic stress as a result of the influence of shock and stretching forces very well.

Keywords*: experimental research, modelling, conveyor belt, conveyor belt stenting.*

Jedną z głównych przyczyn uszkodzeń taśm przenośnikowych są naprężenia dynamiczne, które często prowadzą do zakończenia cyklu życia taśmy. Naprężenia dynamiczne powodują pojawienie się funkcji wytrzymałości zmęczeniowej w warunkach oddziaływania na taśmę tkaninową obciążenia ścinającego. Problem uszkodzeń taśm przenośnikowych można rozwiązać prowadząc obszerne badania doświadczalne w warunkach laboratoryjnych na skomplikowanych, specjalnie do tego celu stworzonych urządzeniach. Celem prezentowanej pracy było określenie zależności między siłami w taśmie przenośnika a masą materiału spadającego na taśmę oraz wysokością zrzutu, w oparciu o dane z przeprowadzonych badań doświadczalnych. Pomiary eksperymentalne przeprowadzono na stanowisku badawczym zaprojektowanym w Instytucie Logistyki i Przemysłu Transportowego FBERG w Koszycach. Wyniki modelowania matematycznego wyraźnie pokazują, że proponowane modele regresji bardzo dobrze opisują rzeczywiste zachowanie taśm przenośnikowych podczas procesu produkcyjnego, w trakcie którego poddawane są one dynamicznym naprężeniom w wyniku oddziaływaniasiły uderzenia oraz sił rozciągających.

Słowa kluczowe*:badania eksperymentalne, modelowanie, taśma przenośnika, stentowanie taśmy przenośnika.*

1. Introduction

Belt transport is a high performance transport system which has a wide application in praxis. The conveyor belts represent the most productive, and thus even the most economical transport device with a high transport performance and ecologic harmlessness. By Kulinowski [17] for belt conveyors, the transport task can be defined as a process whose purpose is to transport the set quantity of handled material within a defined time between the set loading and offloading locations.

From the point of belt conveyor operation the most important construction element is the conveyor belt. Conveyor belt is a closed element, which orbits around the end of drums and also it forms the support and traction element of conveyor belt. Rope belt conveyors are the only exceptions where the belt is only a load bearing element and the rope has a tow function. According to Zur, belt conveyor is a limited range, continuously moving transport facility that carries material on the belt surface, between two belts or inside a belt [28]. According to Marasová [20] conveyor belt carries resistances arising from the movement and serves for transportation of material, loads or people.

During the operation, conveyor belt is influenced by many different stresses, which cause the process of damaging and wearing the belt. Wearing of conveyor belts depends on many factors, but mainly on the operating conditions in which the conveyor belt is working and on the kind of transported material [15, 20, 26, 27]. The operating experience shows that the most critical point, where 66 to 80% of all the damages of conveyor belt arise is the place of feeding, so called dunes. A point impact load, which is one of the main reasons of damaging of conveyor belt is formed at dunes. This point load arises from sharp-edged pieces conveyed material on the conveyor belt. If the energy of impact is greater than the ability of supports and a conveyor belt to absorb this energy, conveyor belt gets damaged mainly in its upper cover layer in the form of transverse and longitudinal grooves, injections and punctures.

The theoretical knowledge, experimental measurements and operating experience shows that the speed and the way of damaging the conveyor belt at the places of dunes depend mainly on itself design of belt and on character of design elements, from which the belt is made. It also depends on the power situation in belt, exactly in the part, where the action of point-forces begins and on the stiffness of the supporting elements of the belt.

Among the functional features of conveyor belts the importance also lies in the tensile strength and resistance of conveyor belts to deflection which is classified as conveyor belt ability to absorb impact energy waist emerging at the impact of the material on the belt, i.e. to absorb the energy shock through deformation work of the conveyor belt without its damaging. In theory, the authors effort is focused on the creation of mathematical models to describe the characteristics of the conveyor belt. Mathematical apparatus for determining optimum reliability and durability of conveyor belts using the theory of recovery was described in the works [24, 25]. The issue of damaging conveyor belts is concerned in many works [9, 10, 22, 23].

The models of punctures rubber-textile conveyor belts have been marginally addressed in the works [2, 3, 4, 5, 13, 14]. Nowadays a significant attention is devoted to mathematical modelling using finite element method [16, 18, 19]. Research of damaged conveyor belts can be implemented at two levels: directly during the operation of conveyor belts, or through special test equipment .Aldrich et al. [1] were realising research of conveyor belts damaging in praxis by using of machine vision and kernel methods. In contrast to it, Fiset and Dussault [11], Ballhaus [6, 7] and Flebbe [12] have analysed the causes of conveyor belts damage in laboratory conditions.

Experimental research in laboratory conditions provides considerable information about the properties of materials. Therefore, the impact tests on laboratory instruments have become a common testing method. In these tests there are forces acting on the sample measured during impact in most cases continually during the test period. Results contain complete information of absorbed energy and deformation of the sample. Currently there are no established uniform criteria for assessing the resistance of conveyor belts against punctures. There are numbers of experimental machines and equipment on which tests on resistance of conveyor belts to deflation were performed.

2. Methodology of experimental research

During operational measurements either directly during operation of a conveyor belt or during measuring of effects of tested samples it is possible to determine force effect on to the individual construction parts of the conveyor belt, such as roller table. However, during operational measurements it is not possible to determine any external load arising, which caused these force effects. And that is why the experimental measurements begin on experimental equipment, where it is able to exactly determine weight of impact load, impact height and forces acting on the belt at the moment of load impact.

A test rig for puncturing tests of conveyor belts was designed and constructed at the Institute of Logistics and Transport Industry in Košice several years ago. According to the gained experiences a laboratory was created later on. It serves to simulation and modelling of structural parts of conveyor equipment including conveyor belts and modern experiment equipment for testing conveyor belts from the point of their resistance to puncturing [20].

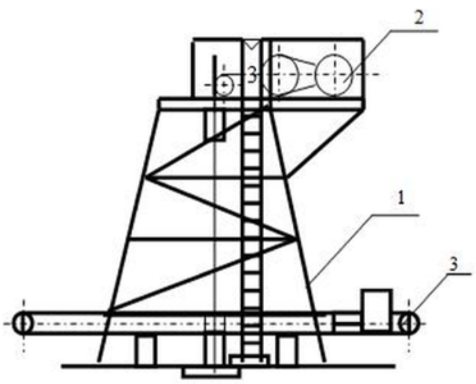

Fig. 1. Side view of the existing structure of test equipment 1 – Tower (mast), 2 – reel device of ram, 3 – belt conveyor

The original device (Fig.1) was upgraded later on (Fig.2). For testing rig a concrete foundation with a grill for attaching the tower, control room for operating the machine and test rig itself were built for the testing rig in advance.

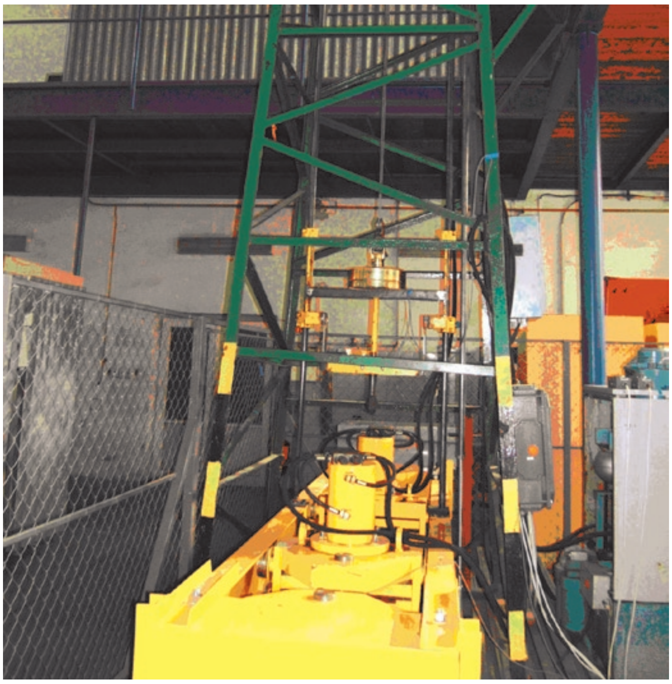

Fig. 2. View of innovated test rig

The test rig is equipped with a hydraulic system for clamping strip samples (Fig.3) and other hydraulic system for tensioning the sample during the test. Hydraulics provide the better clamping and tensioning strip samples and thus allows to obtain relevant test results. The design of the test equipment is based on the current requirements resulting from the present research, as well as from the requirements of the manufacturer of conveyor belts in Slovakia.

Fig. 3. Test table with hydraulic rig

During the realization of the experiment the following parameters can change:

- *weight of the ram* – in the range from 50 kg to 100 kg (simulation of different density of the transported material)
- *ram head* – a spherical shape (Fig.4), pyramid and cone (simulation of different types of impact material)
- *the amount of impact ram* – up to 2.6 meters (simulating the impact of different heights at belt conveyor)
- *type of conveyor belt* (simulation of different operating conditions for which different types of conveyor belts are intended).

Fig. 4. Globular head ram

3. Result and discussion

3.1. Material and realization of the experiment

The research was conducted in order to determine the actual values of impact and tension forces simulating operational conditions and comparing them with those obtained by regression models. Experimental measurements have been performed on a test rig shown in Figure 2.

The objects of experimental tests were steel cord conveyor belts STEELBELT type (Fig. 5) produced in the Slovak Republic.

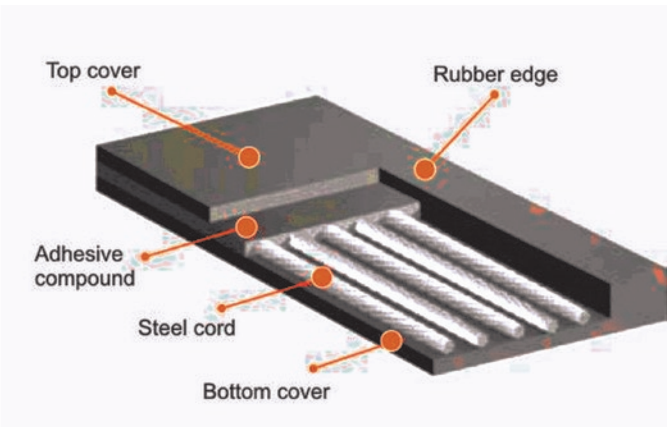

Fig. 5. Cord conveyor belt

Conveyor belts STEELBELT (Fig.5) are suitable to transport material over long axial distances in difficult working conditions. Low elongation under load and their excellent ability to adapt to the conveyor trough due to low transverse stiffness make them suitable for their use mainly in demanding conditions [21].

The skeleton is composed of high-strength steel reinforcing cords laid one plane and coated in rubber core, which provides a perfect blend of top and bottom coating. This hardback ensures optimal functional ability and high durability. Shift cords by selected spacing can be achieved by different strength council. Coatings protect the frame of the conveyor belt against external climatic environmental influences and mechanical damage. Coatings come into contact with the conveyor rollers and drums and protect the skeleton from the adverse effects of abrasion.

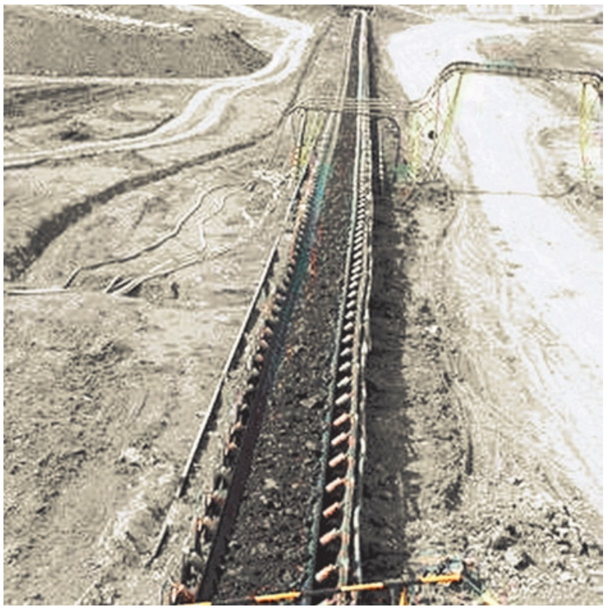

Fig.6. Conveyor belts STEELBELT in use

Ram head with spherical shape and two types of steel cord conveyor belts were used during testing: conveyor belt type ST 1250 with strength 1250 $N.mm^{-1}$ and conveyor belt type ST 2500 with the strength 2500 $N.mm^{-1}$.

The procedure for experiment is as follows:

1. A specimen with a length from 1.2 m to 1.4 m and a width from 0.4 meters to 0.6 meters is cut out from the conveyor belt.
2. The specimen of the conveyor belt is fastened into hydraulic jaws on both sides.
3. It is stretched by the force equal to 1/10 of strength of the belt set by the manufacturer by using hydraulic equipment.
4. The drop-hammer of the relevant weight is lifted by a pulley block to the required height, from which it is released by free fall onto the conveyor belt. During which values of the tension and impact force in kN units are recorded during the whole measurement by two tens-meter sensors.

Evaluation of tests in case of puncture detection consists in a visual inspection of conveyor belt. Meanwhile, it is also determined at what size of tensile force F_S and impact force F_I the puncture of a belt i.e. damage of a belt was caused from the recording of measured data (Fig.7).

3.2. Analysis and design of experiment regression model

Evaluation of the results of the process of damaging the conveyor belt by puncturings is based on long-term follow-up and subsequent statistical evaluation of measured data. In modelling the process of

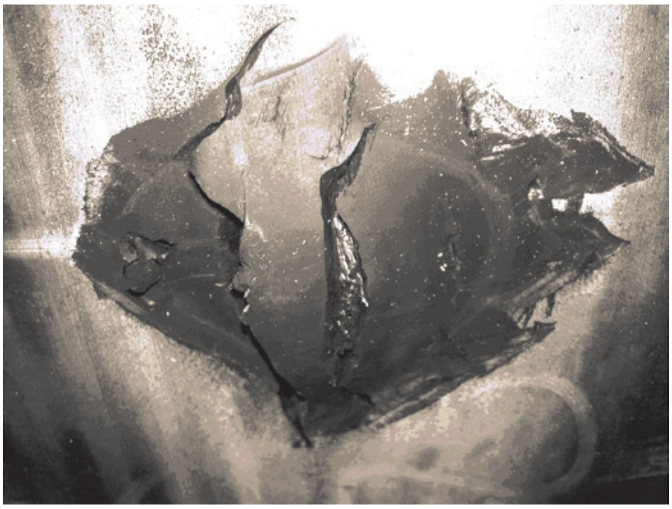

Fig. 7. Damage of a conveyor belt in a way of an impact break

degradation, we used basic statistical methods and multiple regression analysis. To estimate the coefficients of the selected regression model we used the method of least squares. Determining of the close dependence among quantitative variables was considered by a correlation analysis.

The relationship between variable y and several independent variables x_j, $j = 1, 2, \ldots, k$ can be expressed by the multiple linear regression model in the form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \ldots \beta_k x_k + \varepsilon \,, \quad (1)$$

where:

β_0 and β_j for $j = 1, 2, \ldots, k$ – parameters of regression model,

ε – random error [8].

Point estimate of the multiple linear regression model is the regression function:

$$Y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + \ldots + b_k x_k \,, \quad (2)$$

where:

Y – theoretical, estimated value of the dependent variable,

b_0 – the estimated parameter β_0.

The parameters of the regression model are estimated using the method of least squares to which it applies:

$$\sum_{i=1}^{n} \left(y_i - Y_i \right)^2 = \sum_{i=1}^{n} e_i^{\,2} \to \min . \quad (3)$$

where: $e_i = y_i - Y_i$.

The aim of the experiment is to determine the dependence of impact force F_I, respectively tension force F_S from independent variables *Weight of the ram* (m) and *The amount of impact ram* (h) . The best results showed a regression model, which is originated from the regression function in the form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon \,, \quad (4)$$

where variables x_i, $i = 1,2,3$ we chosen in the following way:

$x_1 = m, x_2 = h, x_3 = m \cdot h$ and $y = F_I$, resp. $y = F_S$.

Adjusted regression model has the form:

$$Y = b_0 + b_1 \cdot m + b_2 \cdot h + b_3 \cdot m \cdot h. \quad (5)$$

The method of least squares as a method of estimating parameters of a regression model is very sensitive to the presence of extreme outlying points in the sample. Therefore, at the beginning of the regression analysis, we assessed the quality of the data for outlying and extreme values. Values considered as outliers were excluded from the field. Outlying values were mainly those values, which are beginning to show damage to the conveyor belt, respectively there has been a breakdown of the conveyor belt.

To verify the statistical significance of the regression model we **use the F – test the statistical significance of the model**. The null and alternative hypotheses are: H_0 *: regression model is not statistically significant* against H_1 *: regression model is statistically significant*.

The test statistics is computed using the form:

$$F = \frac{(n-k-1) \cdot \sum_{i=1}^{n} \left(Y_i - \overline{y} \right)^2}{k \cdot \sum_{i=1}^{n} \left(y_i - Y_i \right)^2} \,, \quad (6)$$

where:

y_i – i^{th} observed value of dependent variable,

Y_i – i^{th} estimated value of dependent variable using the regression model,

$\overline{y}$ – mean of the dependent variable,

k – number of independent variables,

n – number of observations.

If the null hypothesis is true, the test statistics F is an observed value of an F distributed random variable with k and $(n-k-1)$ degrees of freedom. The null hypothesis is rejected at the level of significance α, if $F > F_{1-\alpha}(k; n-k-1)$. In case of rejection of the null hypothesis at least one explanatory variable has a statistically significant effect on the test explained variable.

Statistical significance of the regression model parameters will be verified by testing **the statistical significance of regression parameters** β_j. The null and alternative hypotheses are: H_0 *: parameter of regression model is not statistically significant* against H_1 *: parameter of regression model is statistically significant.* The test statistics computed using the form:

$$t = \frac{b_j}{s_{b_j}} \,, \quad (7)$$

where b_j is the point estimate of the parameter β_j and s_{b_j} is the estimated standard error. We reject the null hypothesis at the level of significance α, if $|t| > t_{1-\frac{\alpha}{2}}(n-k-1)$.

In hypothesis testing acceptance or rejection of the null hypothesis can be carried also by decision rule for a p-value. If p-value is less than the level of significance α, the null hypothesis is rejected. If p-value is greater than the level of significance α, the null hypothesis is accepted.

Conveyor belt type *ST 1250*

Point estimate a linear regression model that captures the dependence of impact force from selected independent variables has the form:

$$F_I = -1.2873 + 0.0588m - 0.7945h + 0.1313m \cdot h \; . \quad (8)$$

To check the statistical significance of the model, we used the F – test of the statistical significance of the model. Because $p - value << \alpha$, we assume that the proposed regression model is statistically significant. Statistical significance of each parameter regression model has been verified through a test of statistical significance of the regression parameter. The results show that all of the parameters appear to be statistically significant (Table 1).

Table 1. Estimates of the parameters of a regression model for conveyor belt type ST 1250

Parameter	The point estimate	The lower limit of 95% of the estimate	The upper limit of 95% of the estimate	p-value	Statistical significance of the parameter
b_0	−1.2873	−1.9506	−0.6241	0,0004 <α	significant
b_1 (m)	0.0588	0.0490	0.0687	9,94.10^{-14}<α	significant
b_2 (h)	−0.7945	-1.3303	−0.2584	0,0049<α	significant
b_3 (m.h)	1.1313	0.1225	0.1401	1,1.10^{-25}<α	significant

Multiple index value determination is $I^2 = 0.9981$, which means that 99.81% of the variability of the variable F_I can be explained by the influence of the variables *Weight of the ram*, *The amount of impact ram* and their interaction.

Analogically, we obtain regression models for tensioning force. Model has the form:

$$F_S = 22.5681 + 0.2407m + 4.8752h + 0.1929m \cdot h \; . \quad (9)$$

The obtained model and parameters of the model are statistically significant. Multiple index value determination is $I^2 = 0.9827$, which means that 98.27% of the variability of the F_S can be explained by the influence of the variables *Weight of the ram*, *The amount of impact ram* and their interaction.

Conveyor belt type *ST 2500*

Parameters of the regression model for conveyor belt type ST 2500 and the value of the index determination for the impact and tension force are shown in Table 2.

Table 2. Point estimates of the regression model for conveyor belt type ST 2500

Force	Point estimates of regression model	Index determination
F_I	$F_I = -1.5635 + 0.0687m - 1.3970h + 0.1341m \cdot h$	0.9987
F_S	$F_S = 44.6561 + 0.2153m + 7.3865h + 0.1004m \cdot h$	0.9860

Graphical representation of the measured (empirical) values and calculated (theoretical) values of impact force and tension force to the belt ST 2500 is on Figure 8.

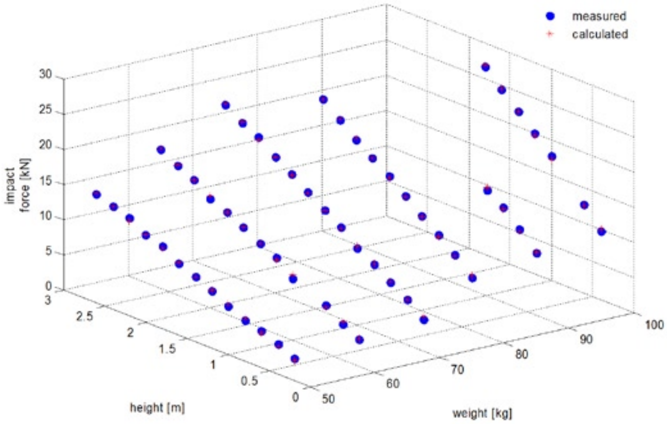

Fig.8. Measured and calculated values of impact force –conveyor belt type ST 2500

3.3. Evaluation of the experiment

Two types of steel cord conveyor belts were considered during modelling and experimental research: conveyor-type ST 1250 with strength 1250 N.mm^{-1} a conveyor belt type ST 2500 with strength 2500 N.mm^{-1}. From measurements, which have been performed on a test rig and ram with spherical tip the following conclusion has resulted:

- cross section of the conveyor belt type ST 1250 appears at a ram of weight:

  $m = 60\ kg$ at its impact from the height $h = 2.2\ m$,
  $m = 70\ kg$ at its impact from the height $h = 1.8\ m$,
  $m = 80\ kg$ at its impact from the height $h = 1.6\ m$,
  $m = 90\ kg$ at its impact from the height $h = 1.4\ m$,

- cross section of the conveyor belt type ST 2500 appears at a ram of weight:

  $m = 80\ kg$ at its impact from the height $h = 2.2\ m$,
  $m = 90\ kg$ at its impact from the height $h = 2.0\ m$,
  $m = 100\ kg$ at its impact from the height $h = 1.8\ m$.

In both cases is can be concluded that size of the energy needed to breakdown of the conveyor belt can be compared with a potential energy of the load impacting the conveyor belt.

Potential energy [J], where the acceleration due to gravity, in the case of the conveyor belt ST 1250 is in the range $\langle 1\,236, 1\,295 \rangle$ J of the conveyor belt in the case of ST 2500 is in the range $\langle 1\,727, 1\,766 \rangle$ J. These values are roughly threshold energy at which it is possible to breakdown the conveyor belt.

The mentioned values are only approximate because the values were measured with difference by weight and the amount of impact. The conveyor belt might have been punctured at the levels that were outside the scope of measurement. Due to a more accurate estimate of limiting energy causing puncturing the conveyor belt, it will be necessary to carry out measurements with smaller differentiate weight or maybe with higher impact.

4. Conclusion

Experimental tests provide not only the information about a process of degradation but even data necessary for their subsequent use in mathematical modelling.

One of the special methods was carried out in the experimental research-the method for determining the resistance to deflection. That method was used because puncturing on conveyor belts often occurs during the transport of a material with large fragmentation, and thus decreases their tensile strength, which is the most important parameter of the conveyor belt in terms of reliability.

On the basis of the facts mentioned above, the important fact is that for a subsequent evaluation of measured data it is able:

- to use a created mathematical model directly without checking other models,
- based on the model created with specific coefficients to determine sizes interpolation of shock, respectively tension forces even for other impact heights and ram weights,

through the methodology used within solution of problems to provide manufacturer with an ability, to set technical parameters of types conveyor belts put out by them for technical praxis, taking operation conditions into account.

Both experimental research and modelling of conveyor belts are important for producers as well as for users of conveyor belts. Users are free to reconsider the way of choice of type and construction of their conveyor belt. Determination of impact energy threshold, at which the breakdown appears, thus destroying DP has practical significance for the user. He can directly set impact height in the place of dunes and regulate the maximum weight load with shredders in the operation and thus not to achieve or exceeded the size of the marginal impact energy. Manufactures got an opportunity to try new design and develop new and more resistant structures of conveyor belts.

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