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Experimental study of the correlation between the conveyor belt structure and the belt puncture resistance

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Abstract
This paper deals with the issue of puncture resistance of rubber-textile conveyor belts. The analysed belts were of identical strengths, but each with a different carcass structure: without an additional anti-puncture layer (breaker layer), with a single anti-puncture layer made of the same material (polyamide), and with an extra anti-puncture layer made of a special material (aramid). In order to achieve a puncture, threshold values of the impact height and the weight of the impacting material were applied. The output of this paper is the determination of a correlation between the conveyor belt structure and the puncture resistance of the belt. The experimental research indicated that the anti-puncture layer (a breaker) is crucial for the elimination of damage to the belt in the form of a puncture.

Keywords
conveyor belt, breaker layer, conveyor belt deflection, regression analysis

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1. Introduction

Belt conveyors rank among the crucial equipment used for the continuous transport of materials in underground and surface mining (Gladysiewicz and Konieczna, 2016). They must be reliable and of high performance. Issues related to the monitoring of the entire belt conveyor were discussed by Wodecki et al. (Wodecki et al., 2016). A conveyor belt is one of the key elements of a belt conveyor. Belts are made of various materials, and they have been attracting the great attention of scientists and researchers (Ryba et al., 2024). Damage to conveyor belts typically causes significant financial costs for conveyor utilisation. The monitoring of belt damage has been studied by many authors. A review of the individual types of damage was presented by Bortnowski et al. (2022). In Poland, the BeltSonic ultrasound system was developed for the diagnostics of degradation processes that occur in conveyor belts (Kirjanow-Blazej, 2023). In a paper by Stachowiak et al. (2021), an algorithm for damage detection is described. Wang et al. (2024) used the Hybrid Local algorithm and the Global Features Network to identify belt damage. In a paper by Trybala et al. (2020), a belt conveyor condition was monitored using a terrestrial laser scanner. The authors in Jurdziak et al. (2024) conducted the same diagnostics using the DiagBelt system, which they had developed. Visual detection of damage was used by Wang et al. (2023). Other authors conducted the detection of belt damage by applying deep-learning methods (Zhang MC., Zhang, Y. et al., 2021; Guo et al., 2021; Zhang MC., Shi H. et al., 2021), (Kirjanow-Blazej and Rzeszowska, 2021). Zhang et al. (2022) used images from a binocular camera to prevent damage to conveyor belts used in the mining industry. In papers Blazej et al. (2013) and Wang BM et al. (2024), various systems were used to identify damage to steel-cord conveyor belts. Damage to conveyor belts is caused by multiple factors. Such damage may be assessed by applying various methods. The identification of damage is part of multiple experimental and numerical studies (Rana et al., 2019). Fedorko et al. (2016) analysed the damage to carcases of conveyor belts using computer metrotomography. Jurdziak et al. (2023) analysed a transverse profile of belt damage. Transverse damage to conveyor belts was examined in papers (Kellis, 2020), (Bajda and Hardygora, 2019), (Dwivedi et al., 2023), (Che et al., 2021), (Leite et al., 2024). Damage caused by materials impacting the belts at the chutes was discussed in multiple papers (Kovanic et al., 2021), (Komander et al., 2016), (Hrabovsky et al., 2024). When the conveyor parameters are set incorrectly, such damage may give rise to an undesired type of damage – a belt puncture. A puncture may result in total decommissioning of the belt.

The main purpose of this article is to analyse the impact of various types of structures of a conveyor belt carcass on the belt resistance to a serious type of damage – a puncture.

2. Materials and methods

2.1. Experimental research

A perpendicular impact of an object onto a conveyor belt results in the formation of impact forces that cause deformation of and damage to the cover layers or even the disintegration of the whole conveyor belt structure. The transported material physically contacts the conveyor belt for several hundredths of a second, while the force acting against the conveyor belt throughout that period is several times stronger than the weight of the material. Experimental research presented in this article included a comparison of different types of carcass structures in terms of the belt resistance to punctures.

2.2. Experiment execution

Experiments aimed at determining the effect of using a breaker layer in conveyor belts (Fig. 1) on the belt resistance to punctures were conducted using three different types of rubber-textile conveyor belts of the P 2000/4 type (with a strength of 2,000 $N.mm^{-1}$ and with 4 textile plies), each with a different type of the carcass structure. The first analysed conveyor belt (CB1) had a carcass with only 4 polyamide textile plies; the second belt (CB2) included an extra polyamide breaker layer; and the third belt (CB3) contained an extra aramid breaker layer. The dimensions of the conveyor belt specimens were as follows: a length of 1.4 m and a width of 0.15 m. During the testing, each belt specimen was stretched with a force F_t=30 kN, corresponding to 1/10 of the belt strength per one millimetre of the belt width. The testing was conducted while using a support system with an idler set (the idler Ø of 92 mm, the idler length of 445 mm, and the idler spacing of 200 mm). The experimental impacts were aimed at the centre between two idlers.

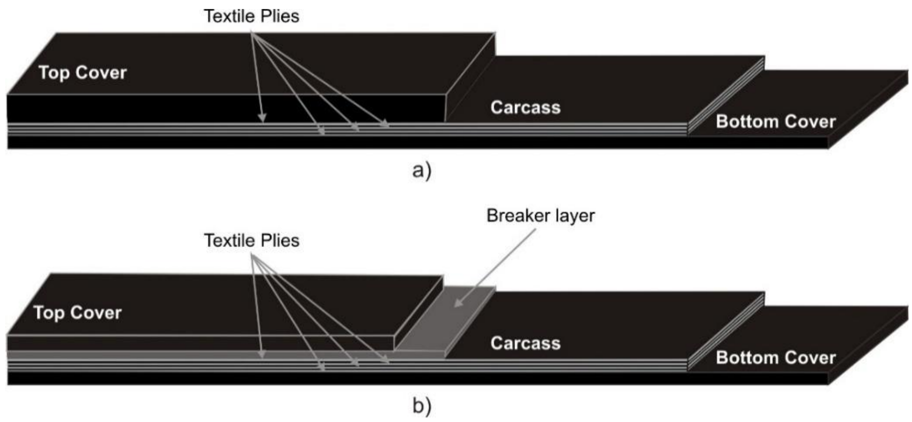

Fig. 1. Types of the analysed belts: (a) without a breaker layer; b) with a breaker layer

The purpose of the experiment was to achieve a puncture and, hence, compare the effect of using a breaker. That is why the experiments were carried out with the maximum usable simulated weight of the falling material (105 kg). Measurements were initiated at an impact height of 2.2 m and continued with 0.1 m increments until the maximum impact height of 2.7 m was reached. Previous experiments verified that no puncture occurred on conveyor belts of the analysed type at lower impact heights. The maximum weight and maximum height were limited by the equipment structure.

2.3 Statistical methods

Results of the experimental research into puncture resistance of conveyor belts were analysed and evaluated by applying basic statistical methods, testing statistical hypotheses, and performing regression and correlation analyses.

In testing statistical hypotheses, two hypotheses were compared against each other: the null hypothesis H_0 and the alternative hypothesis H_1. A decision on rejecting or accepting the null hypothesis is typically made based on the p-value. If the p-value< α, then H_0 is rejected in favour of the alternative; otherwise, H_0 is not rejected.

Correlations between the quantitative variables may be characterised through regression analysis. The assessment of the quality of the relationships between the variables (i.e. the determination of how good those relationships are) was the purpose of a correlation analysis. A statistical analysis was carried out using the R package programme.

3. Results and discussion

The experimental research monitored three parameters: the impact height curve, the tension force, and the conveyor belt deflection formed as the drop hammer impacted the conveyor belt.

In the first step of the process, an analysis of changes in the impact height was made in order to determine the initial hypothesis, which was later subjected to verification through an analysis of the tension force and the conveyor belt deflection. In multiple cases, visual observation indicated that the conveyor belt was still undamaged (the rubber cover layers did not show any visible damage); however, the carcass was actually damaged at that point (Fedorko et al., 2013). Where the carcasses of the tested conveyor specimens were still undamaged, the curves of the impact heights after the individual bounces off the falling material were comparable (Fig. 2). After the carcass suffered damage, the transported material could not bounce to the same heights as those achieved before the carcass was damaged.

3.1 Impact height curve

The evaluation of the results of experimental research into the impact resistance of conveyor belts was also based on long-term monitoring.

At an impact height of 2.2 m with CB2 and CB3 conveyor belt specimens, the bounce heights were comparable (with only little differences). For the CB1 specimen, the bounce heights were comparably lower, indicating that the internal carcass was already damaged. Such damage may easily result in a puncture when the impact heights are higher.

At an impact height of 2.3 m, the situation was very similar to that with a height of 2.2 meters. At an impact height of 2.4 m with the CB2 specimen, the bounce height was lower than that achieved with the CB3 specimen; this indicates that the carcass of CB2 was already damaged, while the CB1 specimen suffered a puncture at 0.70 seconds.

In the case of the CB1 conveyor belt, the specimen was seriously damaged at an impact height of 2.4 m. With the CB2 conveyor belt specimens, serious damage was observed at an impact height of 2.5 m. As for the CB3 conveyor belt, no serious damage was observed throughout the testing, i.e. at impact heights ranging from 2.2 m to 2.7 m (Table 1). Based on the conducted experiments, it may be stated that the resistance of conveyor belts to serious damage increased in the following order: CB1<CB2<CB3. Such a result confirmed our initial hypothesis.

Tab. 1. Result of the experimental research

Conveyor belt type	Impact height [m]					
	2.2	2.3	2.4	2.5	2.6	2.7
No breaker CB1	N	N	SD	-	-	-
Standard breaker CB2	N	N	N	SD	-	-
Special breaker CB3	N	N	N	N	N	N

Note: N /D– no/unserious damage; SD – serious damage, puncture

The curves of the measured heights at the time when the drop hammer with a semi-spherical impactor, weighing 105 kg, impacted the rubber-textile conveyor belts, each with a different internal structure (without a breaker with a standard breaker and with a special breaker) at various impact heights are shown in Fig. 2.

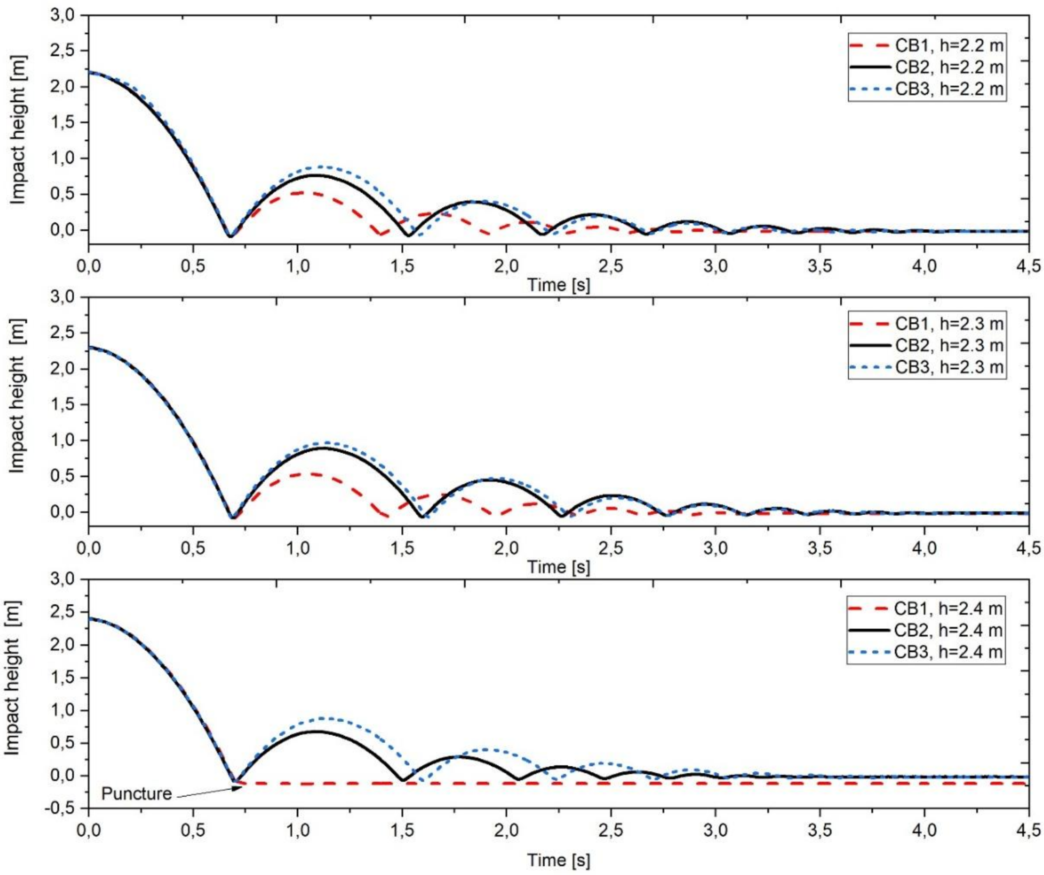

Fig. 2. Impact height curves (m=105 kg)

Therefore, the comparison of puncture resistance of three conveyor belts, CB1, CB2 and CB3, was limited by the impact height. From the impact height of 2.4 m upwards, puncture resistance was only tested for the CB3 conveyor belt because the CB1 and CB2 belts exhibited serious damage – a puncture at lower impact heights. Apparently, the impact of the presence of the breaker layer on the puncture resistance of conveyor belts is not negligible.

3.2 Tension force

For instance, when the material impacts the belt, the tension force increases. When the tension force exceeds a certain threshold, the belt experiences local damage.

For illustration purposes, Fig. 3 presents a graphical representation of the curves of tension force values as a function of time for all 3 types of the tested conveyor belts for the impact heights of 2.3 m (before a puncture occurred on any of the specimens) and 2.4 m (a puncture in the CB1 specimen).

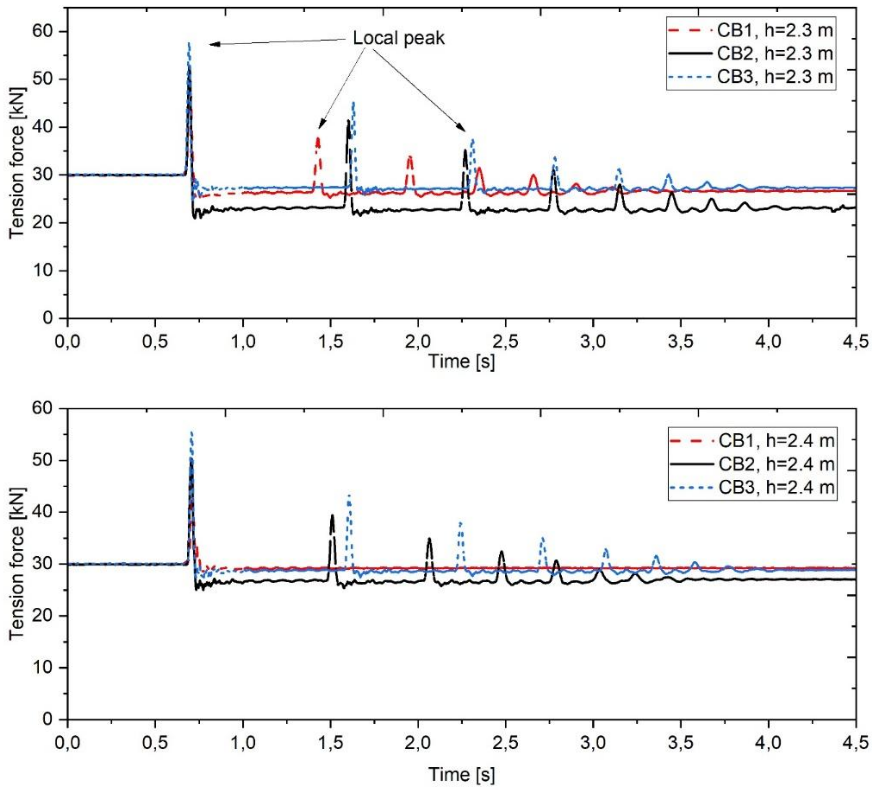

Fig. 3. Tension force curves and local peaks (m=105 kg)

An analysis of the measurement outputs indicated that at an impact height of 2.3 m, the curves of tension force for CB2 and CB3 were not notably different (similarly to the curves of bounce heights), while the curve for CB1 was different, and the main difference is a longer delay. At an impact height of 2.4 m, i.e. the point at which the carcass of CB2 got damaged, CB1 already had a puncture.

In the following step, the values of local peaks of tension force were analysed. Experimental measurements showed that the values of local peaks of tension force decreased over time. To compare the values of local peaks of tension force for the analysed conveyor belts and impact heights, the first 6 local peaks were analysed.

The comparison of the measured values of local peaks of tension force was made by applying the methods for the testing of statistical hypotheses. The Shapiro-Wilk test of normality was used to verify the normality criterion. For each type of conveyor belt and each impact height, a test was conducted to verify whether a set of the measured values of local peaks of tension force satisfied the normal distribution requirement. Since the p-value was higher than α for each selected set, the null hypothesis on the normality of the individual basic sets was not rejected. In the test, all of the selected sets satisfied the normal distribution requirement. The resulting p-values obtained in the testing are listed in Table 2.

Tab. 2. Results of the testing (local peaks of tension force) – Shapiro-Wilk test of normality (α =0.05)

Impact height	Conveyor belt type/ p-value		
	CB1	CB2	CB3
2.2 m	0.400> α	0.133> α	0.303> α
2.3 m	0.455> α	0.103> α	0.209> α
2.4 m	x	0.236> α	0.216> α
2.5 m	x	x	0.140> α
2.6 m	x	x	0.286> α
2.7 m	x	x	0.510> α

Note: *x* – values were not measured due to serious damage/puncture

A pairwise comparison of values of local tension force peaks at impact heights ranging from 2.2 m to 2.4 m was made using a pairwise t-test. Higher values of impact heights were not tested because CB1 and CB2 exhibited a puncture. The resulting p-values obtained in the pairwise testing are listed in Table 3.

Tab. 3. Results of the testing (local peaks of tension force) – pairwise t-test (α =0.05)

Impact height	Conveyor belt type/ *p*-value		
	CB1 vs CB2	CB1 vs CB3	CB2 vs CB3
2.2 m	2.10^{-2}	7.10^{-4}	0.246*
2.3 m	1.10^{-2}	8.10^{-3}	0.075*
2.4 m	x	x	7.10^{-4}

Note: **p*-value > α, *x* – values were not measured due to serious damage/puncture

As a rule, if the p-value is higher than the level of significance (p-value>α), then the null hypothesis on equality of the mean values is not rejected. Results of the testing indicated that the differences between the values of local peaks of tension force for the pair of CB2 and CB3 belts at an impact height of 2.2 m and at an impact height of 2.3 m were not statistically significant. On the other hand, at an impact height of 2.4 m, the differences were statistically significant, which may have been caused by the fact that invisible damage to the CB2 carcass began at that point. In the rest of the specimens, the differences were statistically significant (p-value<α).

A decrease in the values of local peaks of tension force over time represents the weakening of tension force $F_{tension,max}$, which was induced by the impact of the drop hammer (Andrejiova et al., 2020). The best model for characterising the correlation between the values of local peaks of tension force and the time of contact between the drop hammer and the conveyor belt for such weakening at a particular impact height and weight of the falling material is as follows (Model I):

$$F_{tension,max} = \gamma_0 e^{t\gamma_1} + \varepsilon, \tag{1}$$

wherein $F_{tension,max}$ (kN) is the output variable that represents the value of local peaks of tension force; t (s) is the time of contact between the drop hammer and the conveyor belt; γ_0 and γ_1 are the regression model parameters, and ε is the random error. The point estimates of g_0 and g_1 parameters of the regression model were made by applying the least squares method. The strength of the analysed exponential correlation was determined using the index of determination I^2. The point estimates of parameters and the index of determination values are listed in Table 4.

Tab. 4. Parameters of regression models – Model I (α =0.05)

Impact height	g_0	g_1	I^2	*p*-value
CB1				
2.2 m	4.064	-0.282	0.959	6.10^{-4}
2.3 m	4.044	-0.269	0.991	3.10^{-5}
CB2				
2.2 m	4.010	-0.183	0.959	6.10^{-4}
2.3 m	4.076	-0.213	0.971	3.10^{-4}
2.4 m	4.052	-0.231	0.986	5.10^{-5}
CB3				
2.2 m	4.117	-0.266	0.997	2.10^{-6}
2.3 m	4.206	-0.242	0.993	1.10^{-5}
2.4 m	4.135	-0.211	0.984	5.10^{-5}
2.5 m	4.147	-0.206	0.988	2.10^{-6}
2.6 m	4.147	-0.206	0.998	2.10^{-6}
2.7 m	4.146	-0.296	0.989	4.10^{-5}

The analysed regression models and model parameters were statistically significant. In all of the cases, the correlation was very strong. Correlation graphs showing the correlation between the values of the first six local peaks of tension force and the time of contact between the drop hammer and the conveyor belt (only in selected cases, for illustration purposes) are shown in Fig. 4.

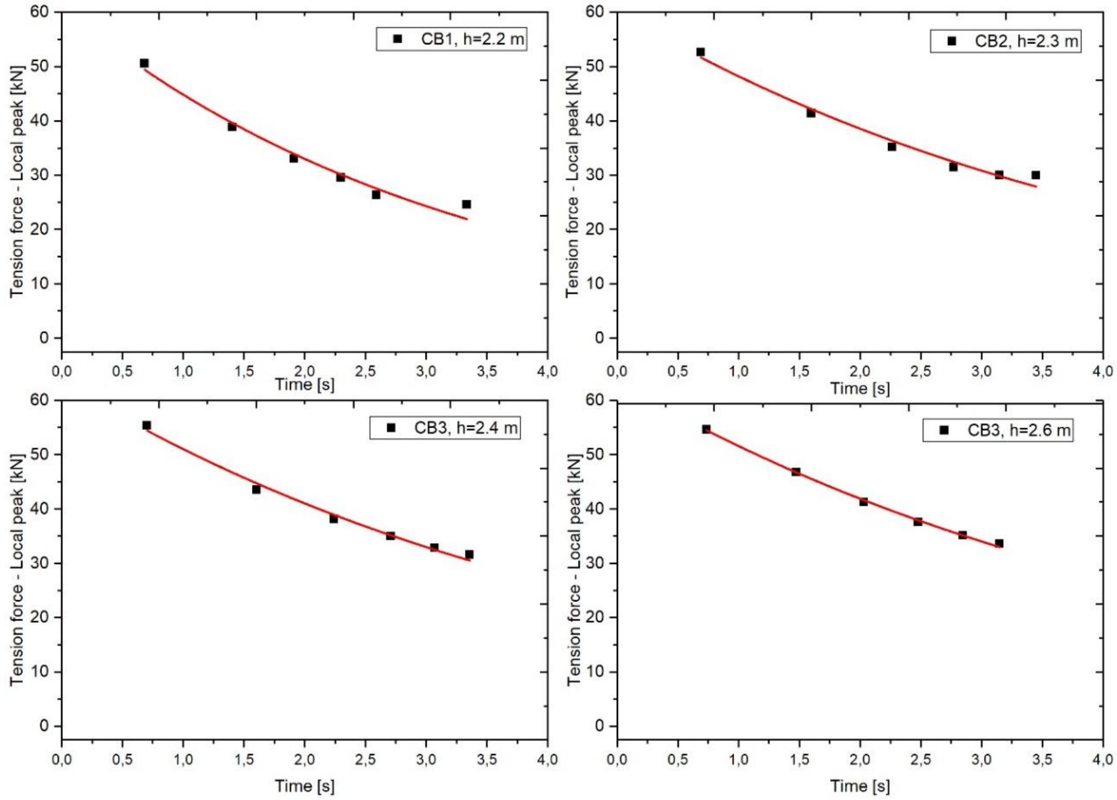

Fig. 4. Correlation graph – Model I

3.3 Conveyor belts deflection

For each recorded measurement, the deflection of the conveyor belt was determined. For the purpose of a more detailed analysis, the selected deflections included those that occurred at the impact of the drop hammer onto the conveyor belt, in particular, the first 6 impacts. A graphical representation of the values of conveyor belt deflections formed at the individual impacts of the drop hammer onto the conveyor belt is shown in Fig. 5.

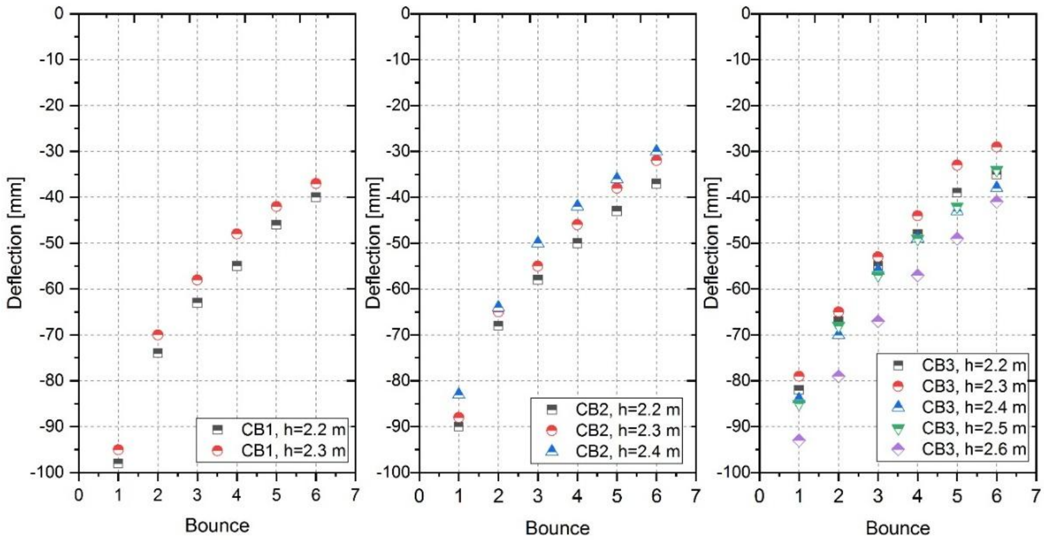

Fig. 5. Deflection of the conveyor belt at the impact site (m=105 kg)

The Shapiro-Wilk test of normality was used to verify the normality criterion, similar to the case of tension force. The resulting p-values obtained in the testing are listed in Table 5. Since the p-value was higher than α for each of the tested sets, the null hypothesis on the normality of the individual basic sets was not rejected.

Tab. 5. Results of the testing (deflection) – Shapiro-Wilk test of normality (α =0.05)

Impact height	Deflection/ *p*-value		
	CB1	CB2	CB3
2.2 m	0.693> α	0.682> α	0.745> α
2.3 m	0.489> α	0.708> α	0.785> α
2.4 m	x	0.634> α	0.652> α
2.5 m	x	x	0.896> α
2.6 m	x	x	0.912> α
2.7 m	x	x	0.768> α

Note: x-values were not measured due to serious damage/puncture

Results of the pairwise comparison of values of deflection at impact heights ranging from 2.2 m to 2.4 are listed in Table 6. Results of the testing indicated that the differences between the values of deflection for the pair of CB2 and CB3 belts at an impact height of 2.2 m and at an impact height of 2.3 m were not statistically significant (as was the case with the tension force). In the rest of the cases, the differences were statistically significant (p-value<α).

Tab. 6. Results of the testing (deflection) – pairwise t-test (α =0.05)

Impact height	Conveyor belt type/p-value		
	CB1 vs CB2	CB1 vs CB3	CB2 vs CB3
2.2 m	1.10^{-3}	3.10^{-3}	0.058*
2.3 m	2.10^{-3}	7.10^{-3}	0.062*
2.4 m	x	x	2.10^{-3}

Note: * p-value > α, x – values were not measured due to serious damage/puncture

Values of conveyor belt deflection showed a rising trend with regard to the time of contact between the drop hammer and the conveyor belt. The best model for characterising the correlation between the values of conveyor belt deflection and the time of impact of the drop hammer onto the CB1 and CB2 conveyor belts at the height of 2.2 m is as follows (Model II A):

$$Deflection = \delta_0 + \delta_1 lnt + \varepsilon, \tag{2}$$

while for the CB3 and CB2 conveyor belts at an impact height of 2.3 m, it is as follows (Model II B):

$$Deflection = \delta_0 + \delta_1 t + \varepsilon, \tag{3}$$

wherein $Deflection$ (mm) is the output variable representing the value of conveyor belt deflection; t (s) is the time of impact of the drop hammer onto the conveyor belt; δ_0 and δ_1 are the parameters of the regression model, and ε is the random error. The point estimates of d_0 and d_1 parameters and the index of determination I^2 are listed in Table 7.

Tab. 7. Parameters of regression models – Model II (α=0.05)

Impact height	d_0	d_1	I^2	*p*-value
CB1				
2.2 m (Model II A)	-85.025	37.374	0.990	4.10^{-5}
2.3 m (Model II A)	-82.042	40.595	0.989	4.10^{-5}
CB2				
2.2 m (Model II A)	-78.084	34.130	0.992	2.10^{-5}
2.3 m (Model II B)	-99.641	19.688	0.993	2.10^{-5}
2.4 m (Model II B)	-98.618	22.618	0.998	2.10^{-6}
CB3				
2.2 m (Model II B)	-98.165	22.618	0.998	2.10^{-6}
2.3 m (Model II B)	-93.753	18.581	0.989	5.10^{-5}
2.4 m (Model II B)	-96.692	17.561	0.997	3.10^{-6}
2.5 m (Model II B)	-99.223	20.178	0.998	2.10^{-6}
2.6 m (Model II B)	-109.923	21.523	0.998	2.10^{-6}
2.7 m (Model II B)	-108.523	24.891	0.999	1.10^{-7}

The analysed regression models and model parameters were statistically significant. In all of the cases, the correlation was very strong. Correlation graphs of the correlation between the values of the first deflections of conveyor belts and the time of impact of the drop hammer onto the conveyor belt (in selected cases) are shown in Fig. 6.

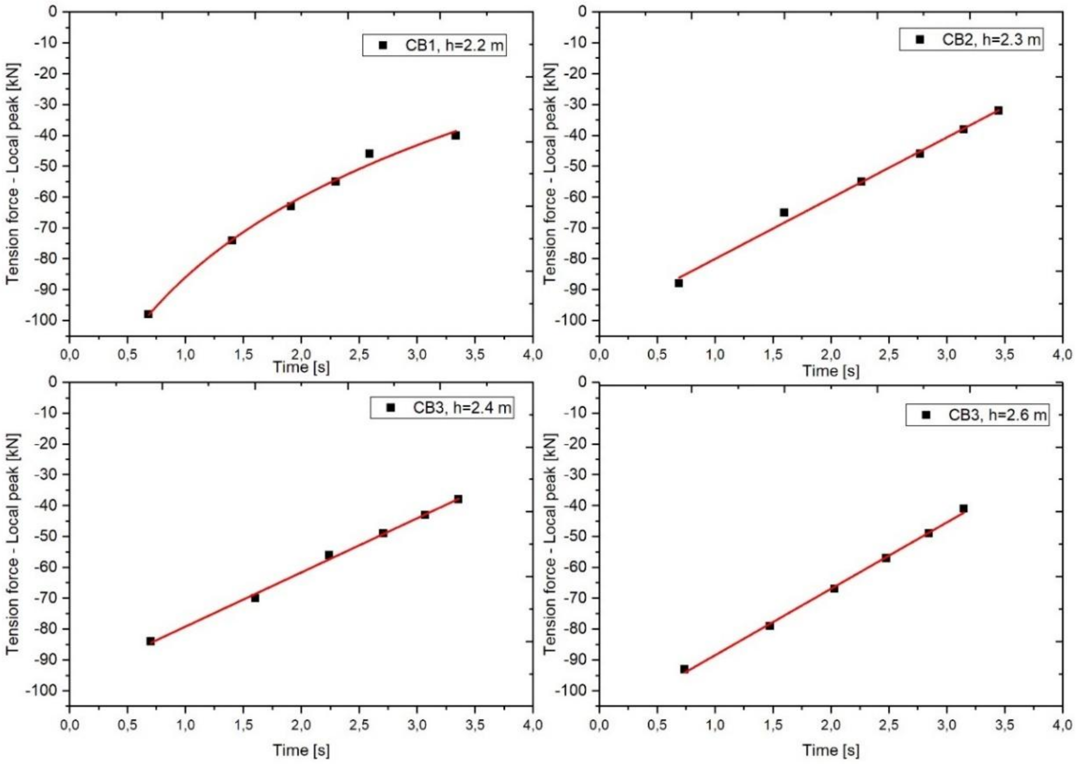

Fig. 6. Correlation graph – Model II

3.4 Correlation between the tension force and the conveyor belt deflection

In the following step, a correlation was analysed between the values of the first six local peaks of tension force and the respective conveyor belt deflection formed at the impact site (Fig. 7).

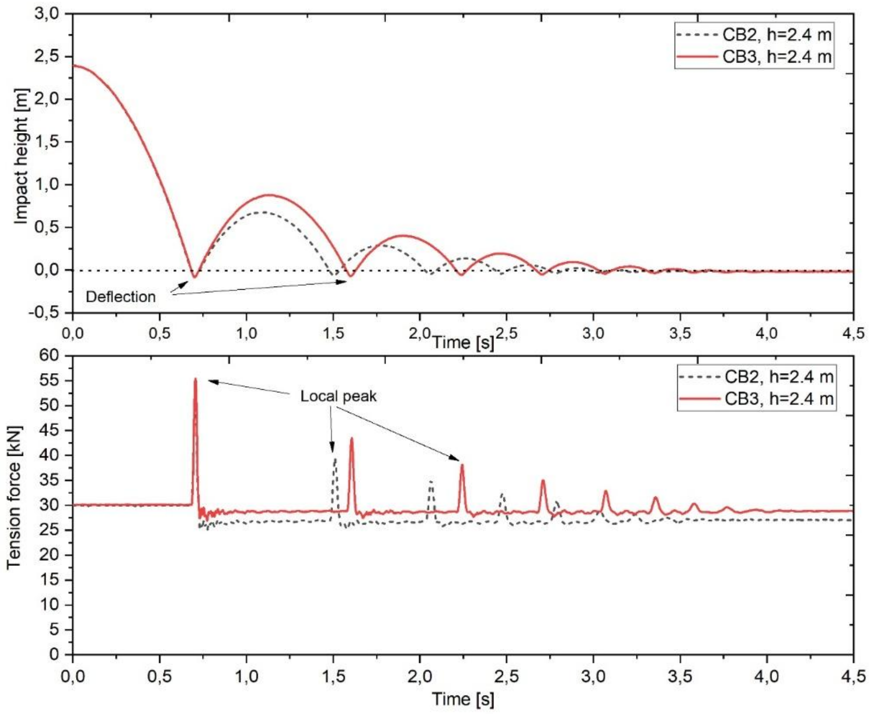

Fig. 7. Conveyor belt deflection and local peaks of tension force (h=2.4 m)

The correlation between the local peaks of tension force $F_{tension,max}$ (kN) and the relevant conveyor belt deflection (Deflection (mm)), as measured at the impact site, is expressed by the following equation (Model III):

$$F_{tension,max} = \beta_0 + \beta_1 Deflection + \varepsilon, \tag{4}$$

wherein β_0 and β_1 are regression model parameters, and ε is the random error. The point estimates of b_0 and b_1 regression model parameters were made by applying the least square method. The strength of the linear correlation was identified using the coefficient of determination R^2.

In order to correctly interpret the Pearson coefficient of correlation R, the normality criterion must be satisfied. That was verified using the Shapiro-Wilk test of normality (Tables 2 and 5). Results of the regression analysis, i.e. the point estimates of parameters, the coefficient of correlation R, and the coefficient of determination R^2, are listed in Table 7. In the case of the CB3 conveyor belt, models were also created for the impact heights of 2.5 m, 2.6 m, and 2.7 m. In all of the cases, the regression model parameters and the regression models were statistically significant (p-value< α).

Tab. 7. Parameters of regression models – Model III (α =0.05)

Impact height	b_0	b_1	R	R^2	p-value
CB1					
2.2 m	5.296	-0.455	-0.996	0.993	2.10^{-5}
2.3 m	12.766	-0.367	-0.998	0.997	5.10^{-6}
CB2					
2.2 m	14.606	-0.390	-0.983	0.967	4.10^{-4}
2.3 m	13.743	-0.427	-0.979	0.959	6.10^{-4}
2.4 m	16.114	-0-394	-0.987	0.975	2.10^{-4}
CB3					
2.2 m	5.086	-0.563	-0.984	0.968	4.10^{-4}
2.3 m	12.338	-0.532	-0.966	0.934	2.10^{-4}
2.4 m	11.024	-0.501	-0.980	0.960	6.10^{-4}
2.5 m	13.501	-0.465	-0.982	0.964	5.10^{-4}
2.6 m	15.237	-0.408	-0.988	0.976	2.10^{-4}
2.7 m	9.493	-0.450	-0.982	0.964	5.10^{-5}

Note: $|R|<0.29$ – no correlation; $0.30<|R|<0.49$ – a weak correlation; $0.50<|R|<0.79$ – a moderate correlation; $0.80<|R|<1$ – a very strong correlation

The point estimate of the model parameters (Table 7) indicated that there is an indirect correlation between the values of local peaks of tension force and the conveyor belt deflection at the impact site ($b_1<0$). The value of the coefficient of correlation indicated that the correlation was indirect and very strong ($0.80<|R|<1$). For example, in the case of the CB1 conveyor belt and the impact height of 2.3 m, as much as 99.7% of the variability of the $F_{tension,max}$ variable was explained by the linear model (R^2=0.997).

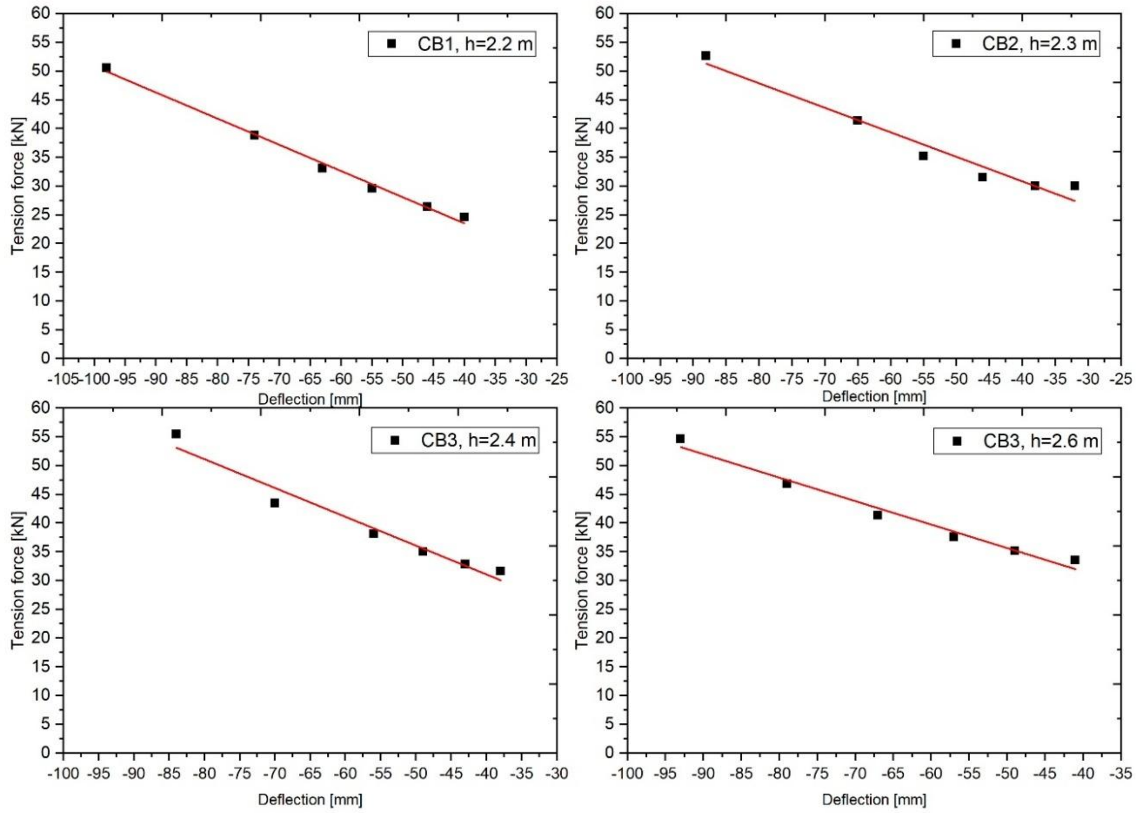

Fig. 8. Correlation graphs – Model III

Correlation graphs of the correlation between the values of the first six local peaks of tension force and the conveyor belt deflection at the point where the drop hammer impacted the belt (in selected cases) are shown in Fig. 8.

4. Conclusion

Experimental testing of puncture resistance of conveyor belts is very important and facilitates faster solving of problems associated with belt damage and ruptures. The determination of a threshold impact height for a material of a particular weight at which the belt is punctured, which may result in the decommissioning of such a belt, has practical meaning for belt users. Maximum heights and weights of the transported material may be set directly at the operation facility, at chute points, in order to avoid damage that might cause the loss of the conveyor belt functionality. The impact of the presence of a breaker layer on the puncture resistance of conveyor belts is not negligible. The absence of such a breaker layer hinders the full utilisation of the conveyor belt's potential under dynamic impact loading. The puncture resistance of conveyor belts may be improved by the presence of a breaker layer made of an appropriately selected material.

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