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New possibilities for testing rubber composites: Design of the fatigue bending test

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ABSTRACT

The study analyzed the influence of various factors on the strength and reliable operation of belt conveyors based on rubber composite material. It was shown that the fatigue strength of composites is a very important factor influencing operation. The degradation process results from the variable load of material between the rollers and the belt tension. This load corresponds to three-point bending with sufficient accuracy. The design of an appropriate attachment that will guarantee such a load during tests on a standard testing machine. Conveyor belts tested in this way can then be safely used in conveyors. In addition, the forces and displacements that will occur during the experiment were considered.

Keywords: reliability of conveyors, cyclic loading, rubber-based composite.

ASSUMPTIONS FOR THE SUPPORT DESIGN

The problem of resistance of structural materials to time-varying loads is an important issue in design. The problem of fatigue of materials makes it possible to predict the life of components and, consequently, to plan the logistics of repair and replacement of worn parts. To ensure the reliability of the conveyor operation, many tasks must be completed. The operational problem can be considered in the drive, the supporting structure, including rollers [1] and conveyor belts. The resistance to movement of the belt conveyor during operation is also very important [2]. The working element of belt conveyors is the conveyor belt, the task of which is to transfer materials. The structural material of the belts is usually rubber, but to improve the strength of the belts, composite structures are used. Conveyor belts are typically rubber composite structures reinforced with layers of glass, polyester, and nylon, designed to meet various operational requirements. It is worth noting that belts with a steel-cord core are also widely used, especially in the applications involving the transport of heavy loads and large forces, such as in mining and heavy industry. These steel-cord belts provide excellent tensile strength and durability, making them suitable for demanding conditions. However, the present study focused specifically on the belts reinforced with glass, polyester, and nylon layers, which constitute the target group of tested materials.

The material of conveyor belts is subject to varying loads during their operation, which changes the belt functionality over time. To obtain the best results during operation, it is necessary to model the loads in advance [3]. This is followed by static [4], fatigue tests like uniaxial tension [5–7] or tension-compression [8–10]. With regard to standard static property tests of materials, the fatigue phenomenon can cause critical damage to the structure with the passage of operating time.

However, some authors use computational models based on the model of the belt deflection line between the conveyor support rollers to analyze the operation of transmission belts [11, 12]. They indicate how the belt deforms between the support rollers by assuming the continuous load on the belt is caused by the material being transported. Considering the design of conveyors, the way the belt works, and the loads from the transported materials, the closest technological test to these conditions is the three-point bending test (Fig. 1).

These tests are performed according to standardized procedures, e.g. ASTM D790 3-Point Flexure Test on Plastics. Manufacturers of standard testing machines offer additional fixtures to perform three-point bend tests as an option to expand testing capabilities. In the case of rubber-based materials, these additional fixtures do not allow the implementation of three-point bending due to the lack of attachment of the test material, and the use of only supports and a punch is not possible in this case. This is a challenge for non-standard tests aimed at providing unusual data (e.g., the temperature of the test object) or attempting to record phenomena occurring in materials and structures in new research areas, expanding knowledge of the material subjected to complex loading conditions or tests requiring new measurement techniques. When looking for a solution in non-standard testing, the first step is often to develop designs for proprietary clamping systems and dedicated measurement systems, as well as determine how to load material specimens or structural components [11, 13, 14].

Other tests that are carried out for this type of composite are the analysis of the effect of vibration on strength [15] or friction [16]. Diagnosing transmission belts during operation [17, 18] and after refurbishment [19] is also an important factor when analyzing the non-water tightness of these devices.

The aim of the work is to present the design of a new assembly for fastening and loading a sample of a transmission belt on a standard single-axis fatigue machine. It was also assumed that the device would allow testing in a pendulum load cycle, making it possible to observe the effects of degradation of the tested sample when the belt was bent in two directions. Fatigue tests can be either displacement or force-controlled.

TEST STAND

The design of an appropriate stand is a preliminary stage for subsequent fatigue tests. These tests were performed on a standard Instron Electropuls E10000 machine (Fig. 2). It is a testing machine with an electrodynamic drive. It is designed to conduct static and dynamic strength tests of samples of various materials (metallic, polymer, ceramic, and composite), as well as finished products. Using pneumatic fixtures, samples and products can be tested in tension, compression, or bending (3- and 4-point). The machine is equipped with the software that allows for measuring the values of displacement and force in the working head of the station and freely configure the forcing in the form of force

Figure 2. Instron Electropuls E10000 test machine

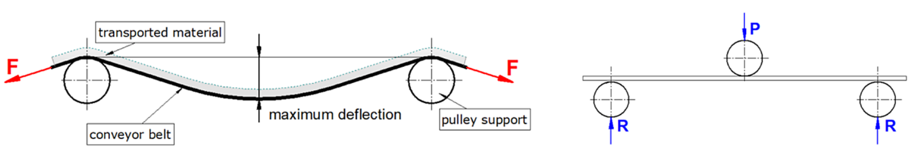

Figure 1. Model of belt deformation and three-point bending load scheme

or displacement. It is possible to conduct tests with controlled displacement of the working head or controlled force loading the tested element. The maximum variable load is ± 10 kN with a maximum frequency of 15 Hz; the average load is possibly ± 7 kN, and the working range of head displacement is 60 mm.

On the basis of the assumptions and research objectives, as well as standard solutions of fixtures intended for the three-point bending test, a diagram of the mounting and loading assembly was developed (Fig. 3). The base (1), as a stationary element, is mounted in the lower handle of the machine. Two symmetrical brackets (2) allow the belt to be supported and fastened using plates pressed with screws. (3) The height of the brackets must ensure free movement of the actuator within ± 30 mm. An additional tensioner (4) between the supports allows the sample (5) to be pre-tensioned to compensate for any slack during clamping or to add additional static stretching.

At this stage, a simplified FEM numerical model of the handle was also developed, which allows for a preliminary assessment of forces and displacements for the tested sample, which helps determine the operating parameters of the machine (Fig. 4). The simulation model for a given actuator displacement allows to estimate the force necessary to cause such a deformation. Additionally, the force in the cross-section of the belt halfway between the actuator roller and the bracket is calculated, constituting the internal force in the tensile sample.

A literature review on the operation of conveyors based on rubber belts and simulation results indicate that in the case of bending of rubber used for conveyors, the deflection caused by belt bending generally occurs near the contact of the belt with the rollers, both in the actuator and the supports. In the remaining part, between the rollers, the belt is stretched. By adopting this assumption, it is possible to indirectly determine the tensile force in the belt by measuring the loading force. For the adopted method of loading the sample, the force balance system can be described in Fig. 5a (and, as an aid to the calculations, Fig. 5b). Here, it should be noted that there is also a slight bending of the belts. The exact distribution of normal stresses is the sum of normal stresses

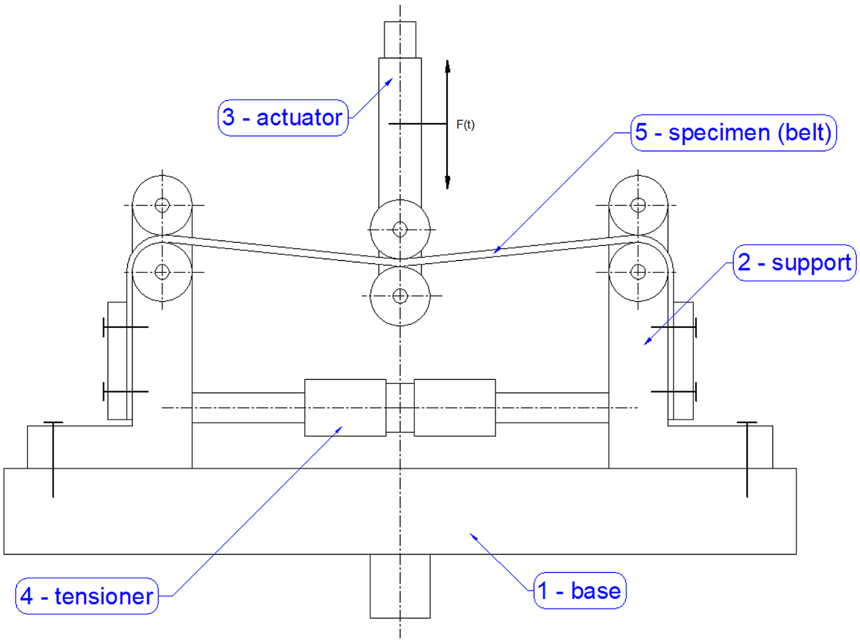

Figure 3. Basic scheme of holder structure

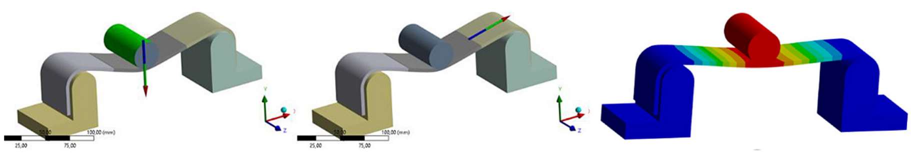

Figure 4. FEM simulation model

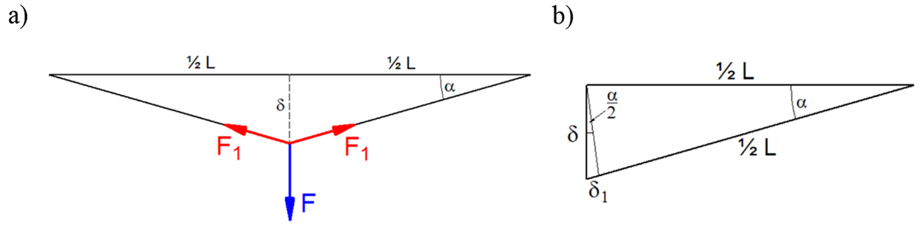

Figure 5. Equilibrium of forces system, where: F – force loading the sample (recorded on an ongoing basis during the tests), F1 – internal force in the sample, L – distance of the support roller axis, δ – displacement of the actuator (recorded on an ongoing basis during the tests)

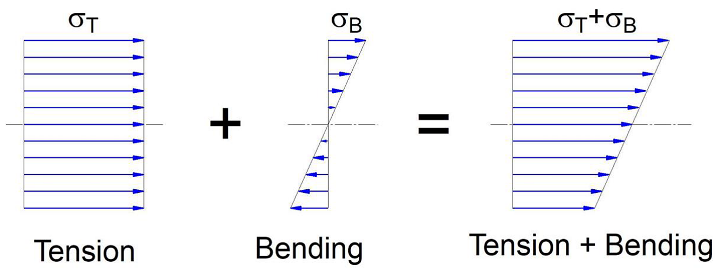

Figure 6. The sum of normal stresses resulting from bending and tension

resulting from bending and tension, as shown in Figure 6. It is expected that the bending normal stresses will be much lower than the tensile stress from prestretching of the specimen. One of the testing outcomes will an estimation of the suitability of the DIC method to exactly capture the stress distribution in the specimen. A detailed finite element analysis and measurements using digital image correlation will be the subject of separate analyses and will demonstrate the importance of these stresses, but they still need to be addressed at this stage.

It should be remembered that in the case of composite materials, such as a rubber belt in conveyors, degradation of the longitudinal modulus of elasticity E occurs during operation [20]. Additionally, in the case of composite materials, large deformations may occur, and the theory of large strains should be applied, i.e., logarithmic strains called "true strain," corresponding to "true stress" [21]. However, the first analyses will adopt an engineering deformation model with linear-elastic characteristics.

Considering the elongation δ_1 of the sample (Fig. 5b) and the force balance conditions (Fig. 5a), the value of the internal force F_1 can be determined. The geometry implies a relationship

$$\delta^2 = {\delta_1}^2 + \delta_1 \cdot L \tag{1}$$

where: L – span, δ – deflection arrow, δ_1 – specimen elongation.

Therefore, with the known span between the supports and the deflection arrow, the elongation of the rubber can be determined based on the formula

$$\delta_1 = \frac{-L + \sqrt{L^2 + 4\delta^2}}{2} \tag{2}$$

In general, the relationship between the strain and the stress can be written for static loads as:

$$\varepsilon = \frac{\sigma}{E} + \alpha \left(\frac{\sigma}{K}\right)^{1/n} \tag{3}$$

where: ε – strain, σ – stress, E – Young's modulus, α – coefficient adjuststing the impact of nonlinearity, K – strength coefficient, n – strain hardening exponent.

And similarly for cyclic loads

$$\varepsilon_a = \frac{\sigma_a}{E} + \alpha \left(\frac{\sigma_a}{K'}\right)^{1/n'} \tag{4}$$

where: ε_a – strain amplitude, σ_a – stress amplitude, K' – cyclic hardening coefficient, n' – cyclic hardening exponent.

The Ramberg-Osgood equation does not account for potential progressive failure mechanisms that can occur in some composite materials. While such phenomena can be neglected for general descriptions of stress-strain behavior, in specific cases, it becomes necessary to include additional terms in the equation or extend it in another way [22]. This is particularly important when dealing with fiber-reinforced composites under complex stress states or specific fiber orientations (e.g., 45°/-45°), where progressive damage, such as microcracking, fiber-matrix debonding, or delamination can significantly influence the material response. Although these effects may not be critical in many practical cases, especially within the elastic domain, for the applications where accuracy in modeling progressive failure is essential, modifications to the original equation are required to reflect the nonlinear or progressive characteristics observed in experiments. Assuming engineering deformations in Equation 3 and, in a first approximation, a linear elastic range (the second part of formula (3) responsible for plastic deformations) resulting in a simple form of

$$\varepsilon = \frac{\sigma}{E} \tag{5}$$

Additionally, when analyzing the properties of a composite material, the relationship between strain and stress should be described using a stiffness matrix. For the plane stress state in orthotropic materials, such an equation would have a form of

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_6 \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\vartheta_{12}}{E_2} & 0 \\ -\frac{\vartheta_{12}}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \cdot \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} \tag{6}$$

However, after assuming that and are equal to zero and analyzing just the stain along the specimen's length, the resulting relationship is identical to Equation 5.

The value of strain also describes the relationship between the elongation and the initial length of the sample, which is expressed in the form

$$\varepsilon = \frac{\delta_1}{L} \tag{7}$$

Equating two expressions describing the strain value (Equation 5 and 7), a formula for the value of the force appearing in the rubber is obtained in the form

$$F_1 = \frac{2\delta_1 AE}{L} \tag{8}$$

where: A – cross-sectional area of the sample.

And substituting formula (2) into it, the form is obtained

$$F_1 = AE\left(-1 + \sqrt{1 + \left(\frac{2\delta}{L}\right)^2}\right) \tag{9}$$

In turn, the value of the force that must be applied to obtain a given deformation state can be written in the form

$$F = \frac{4AE\delta\left(-1 + \sqrt{1 + \left(\frac{2\delta}{L}\right)^2}\right)}{\sqrt{L^2 + 4\delta^2} + L} \tag{10}$$

Here it should be noted that for composites with a constant deflection arrow δ, the force F resulting from formula (6) will vary due to the decrease in the value of Young's modulus E.

THREE-POINT BENDING SUPPORT

On the basis of the adopted assumptions, a CAD model of the handle was developed, as shown in Figure 7.

The use of double roller systems in the brackets and the actuator allows for equal deformations of the belt in the places of deflection when the actuator is moved both up and down. The maximum thickness of the sample is 5 mm, so the upper rollers can move within a range of 5 mm to adjust their position to the thickness of the sample being tested. The required minimum width of the sample is 50 mm – the width of the rollers and other elements results from adopting this condition. The rollers are locked with screws, where the tightening force of the screws is sufficient to immobilize them by the force of friction against the contact surfaces with the actuator head. The conveyor belts of such thickness are intended for less demanding applications, usually indoor logistic applications. This particular case was chosen in order to stay within the loading limits of the applied testing machine. Of course, heavy duty conveyor belts are significantly thicker, with more reinforcing layers and steel cord reinforcements. However, by testing such a heavy-duty belt specimen, not only the loading levels but also the loading apparatus should be much larger, since the minimum allowable bending radius of the heavy-duty conveyor belts is much more than 25 mm (as is the radius of supporting rollers in our case). On the other hand, the phenomenon of damage initiation and propagation until the final failure is similar for both cases. This means that the testing method

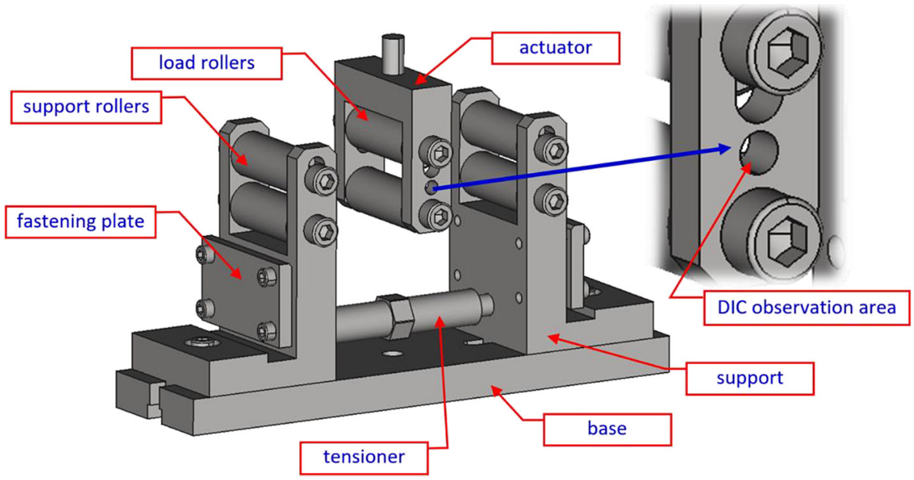

Figure 7. The CAD model of the holder

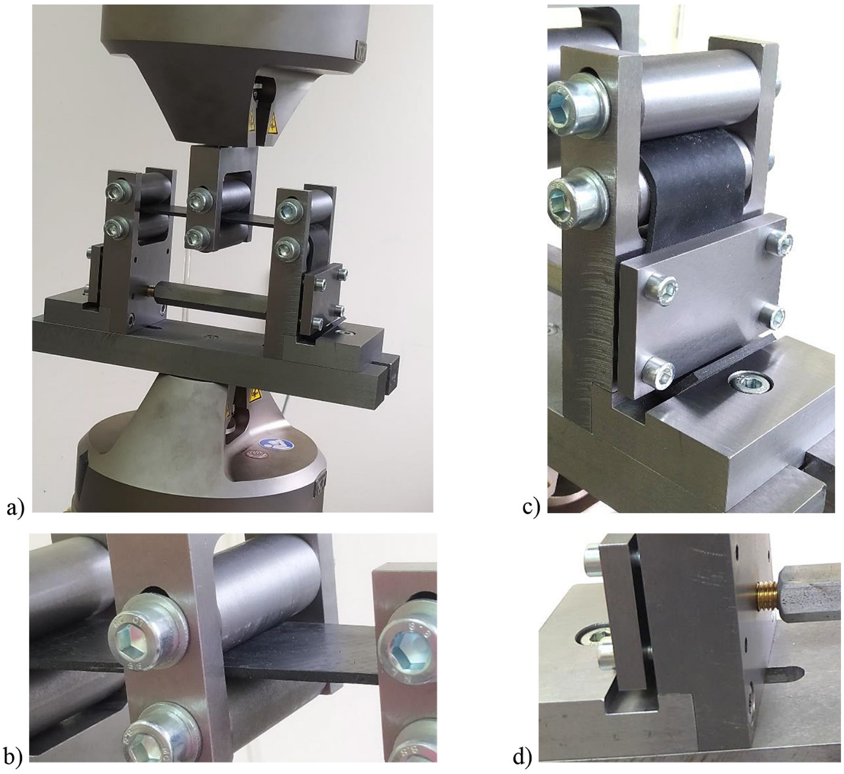

Figure 8. The holder mounted on the machine: a) view of the holder with the attached sample, b) close-up of the sample between the rollers, c) close-up of the sample mounting to prevent it from slipping out, d) close-up of the bracket

and methodology for predicting the service life of such belts can be validated on smaller scale specimens. For this reason, rubber composites with 5 mm thickness were selected for research.

The designed holder is unique to this type of research. There will be a belt bending effect in the area of the load roll as well as at the supports, which may overlap with stretching in the part of the belt between them. During the operation of the device, one will possibly have to react by changing the design of the support and actuator if there is an obvious effect on what happens between the support and the load roll. In addition, before each test, deformations in the specimen can be preliminarily estimated using the developed FEM model.

One of the important stages of research is the observation of phenomena occurring at the inflection points of the sample on the rollers. The use of vision systems and DIC techniques was assumed.

For this purpose, a hole will be made between the rollers to mount the inspection camera head.

Figure 8a shows a view of the handle mounted on the Instron machine. The sample is attached between the actuator rollers (Fig. 8b) after mounting it in the bracket holders and pre-tensioning the belt. The sample is clamped in the brackets with a plate fastened with 4 screws. The surfaces of the mounting plates are smooth, there is a groove under the plate in which the sample is turned outwards (Fig. 8c). This prevents the belt from being pulled out of its mounting. Grooving of the mounting plates was omitted because sharp edges may damage the surface of the belt in the mounting and cause damage to the sample in the holder. The brackets were divided for technological reasons (Fig. 8d). The entire design provides for maximum stiffness of the handle during testing.

CONCLUSIONS

1. The presented specimen holder is characterized by simplicity of design and meets the expectations of fatigue tests for complex belt loading conditions:
- it is possible to evaluate the effects of deformation when the belt is cyclically bent,
- belt preloading can be induced by fixed displacement of supports,
- it is possible to evaluate the degradation of the belt material with the number of fatigue cycles owing to the ability to record the current values of load force and displacement on the Instron machine,
- assuming equilibrium conditions for the forces in the system, it is possible to estimate the forces in the belt by actually measuring the value of the force loading the sample and the displacement of the actuator head,
- It is possible to equip the holder with a vision system (e.g., an endoscopic camera to observe the area where the load is applied).

2. The presented design corresponds to the requirements of the technological test of three-point bending and can be successfully used for other composite materials. The fixing system uses rollers in the supports to allow achieving the full range of machine loading.
3. Detailed experimental tests using DIC and FEM calculations will prove whether the assumption that the belts work only in tension is correct or not.

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